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Validation and calibration of the FARSITE fire area simulator for Yellowstone National Park

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VALIDATION AND CALIBRATION

OF THE FARSITE FIRE AREA SIMULATOR

FOR YELLOWSTONE NATIONAL PARK

By

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THESIS

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ABSTRACT

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Validation and Calibration of FARSITE Fire Area Simulator for Yellowstone National Park (120 p.)

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The FARSITE fire area simulator, which allows for the evaluation of fire behavior in a GIS setting, continually needs validation for various fuel, climate, and terrain conditions. Five fires during the 1994 and 1996 fire seasons burned significant acres in Yellowstone National Park (YNP), providing the information necessary to test the FARSITE model for this area. Results varied between the different fuel models as well as between the different fires, but not between the short, mid, or long-range projections. Results indicate a pattern of over-prediction by FARSITE in fuel models 1, 2 and 5 by a large margin, and moderate over-prediction in fuel model 10 and in some areas of fuel model 8. Other areas delineated as fuel model 8 exhibited under-prediction of fire behavior, indicating a possible problem with the vegetation cover/fuel model classification. Fuel model 5, traditionally used to represent recently burned areas (0-50 years), was determined to be inadequate for recently burned areas, which typically did not burn. While a non-fuel designation may be more appropriate initially, until further vegetation recovery occurs, further research may be necessary to identify the age at which this fuel model change should occur. Validation exercises also indicated a need for improved weather data collection in order to capture more appropriate spatial and temporal wind patterns.

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1.0 INTRODUCTION

The continuing development of fire behavior modeling has provided alternative methods for predicting fire behavior under various conditions. These models have become useful tools in evaluating potential risks and determining appropriate management responses (Finney and Andrews 1998, Andrews 1989). Tools such as the BEHAVE Fire Prediction and Fuel Modeling System, the handheld TI-59 computer, and fire behavior nomograms have become an integral part of the Fire Behavior Analyst toolbox over the past several years (Andrews 1989). The recent addition of the FARSITE Fire Area Simulator to the Fire Behavior Analyst (FBA) repertoire has enhanced the ability of managers to evaluate fire behavior and management actions on the landscape level.

FARSITE is a computer modeling system that simulates fire behavior on a complex landscape by utilizing 3-dimensional GIS (Geographical Information System) data layers. This model provides the opportunity to evaluate the relative sensitivity of fire behavior patterns to changes in weather or fuel conditions. The BEHAVE fire prediction system provides the basic backbone to FARSITE, however this more advanced program requires more intensive data collection and GIS layer preparation prior to its use (Finney 1998, Keane et al. 1998).

As a relatively new model, FARSITE needs to be validated by applying it to various regions, fuels, and climates as well as for various fuels maps and mapping techniques. Multiple studies need to be performed to compare the fire behavior simulation to actual fire behavior on the landscape (Finney 1995, Finney and Andrews 1999). Validation can be accomplished by recreating fire behavior of large fires on complex topography using recorded weather and fire behavior data (Rothermel and Rinehart 1983). Prescribed Natural Fires (PNF), more recently termed "Wildland Fire Use for Resource Benefit" (WFURB; USDA/USDI 1998), provide ideal opportunities for such validation exercises.

During the 1994 and 1996 fire seasons, conditions in Yellowstone National Park (YNP) allowed for large fire growth of several PNFs (prior to the terminology change to WFURB) as well as one wildfire. During the 1994 fire season, the Tern and Raven PNFs burned 4,888 and 3,570 acres, respectively, while the Robinson fire burned 8,514 acres despite suppression efforts. The 1996 Pelican PNF burned 1,524 acres while the Coyote PNF burned 4,271 acres across jurisdictional boundaries with the Gallatin National Forest (1,632 in YNP and 2,639 in the Gallatin NF; YNP Fire Management Records).

Progression maps were recorded for various time periods during the course of these fire events, and final perimeter maps were prepared for each fire. During the active periods of these fires, daily weather observations were recorded and spot weather forecasts were obtained. Occasional notes on fire behavior were also recorded. These fires, and the information recorded during these events, provide an opportunity to test the application of FARSITE to the fuel models in Yellowstone, using known fire behavior and recorded weather data.

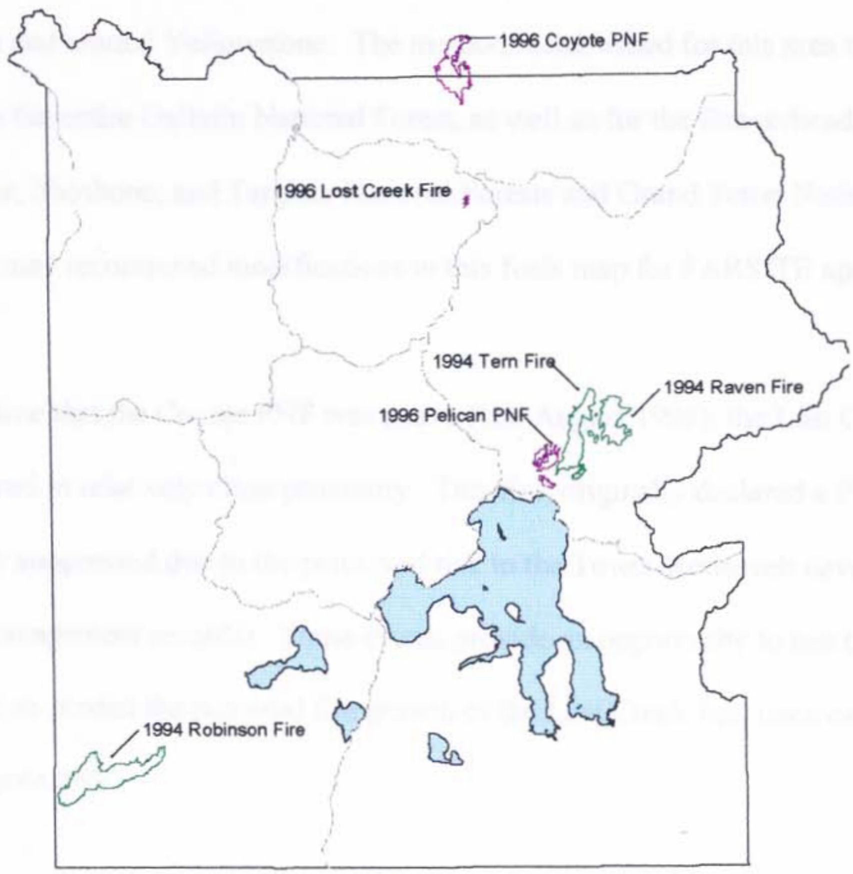


Figure 1.1. 1994 and 1996 large fires in Yellowstone National Park.

For two weeks during the 1996 fire season, a National Park Service prescribed fire overhead team was in the park overseeing all PNF operations. The team attempted to use FARSITE as a planning tool, but efforts were limited by the lack of an established fuels map. The amount of preliminary work needed to set up the necessary data layers for FARSITE precluded further use of this fire behavior tool (Renkin pers. comm.).

This study documents a process for data collection and input for future FARSITE utilization in and around Yellowstone. The methods established for this area may then be applicable to the entire Gallatin National Forest, as well as for the Beaverhead, Bridger-Teton, Custer, Shoshone, and Targhee National Forests and Grand Teton National Park. This project may recommend modifications to this fuels map for FARSITE application.

During the time that the Coyote PNF was active (late August 1996), the Lost Creek Fire was discovered in relatively close proximity. This fire, originally declared a PNF, was subsequently suppressed due to the perceived risk to the Tower-Roosevelt developed area (YNP fire management records). These events provide an opportunity to test the utility of FARSITE to predict the potential fire growth of the Lost Creek fire, once calibrated with the Coyote PNF.

1.1 STUDY OBJECTIVES

1. To validate FARSITE using behavior of known fires from the 1994 and 1996 fire seasons.
2. To calibrate FARSITE to Yellowstone National Park local fuel conditions using behavior of known fires.
3. To evaluate the fuels map, for use in FARSITE fire area simulator.

4. To project the potential fire behavior of the suppressed Lost Creek Fire, once calibrated to the 1996 Coyote PNF.
5. To identify potential fire management applications of FARSITE in the Greater Yellowstone Area.

The results of this study may be used to establish a baseline from which managers in Yellowstone and the surrounding area can better utilize FARSITE as a fire management tool.

1.2 SIGNIFICANCE

Fire behavior modeling has become a critical part of fire management. Through fire behavior prediction, managers may identify conditions under which fire behavior would change. This information could prove vital when fire fighters lives, as well as the public might be in potential danger.

The application of fire prediction tools allows for better evaluation of appropriate management responses to wildland fire. Tools such as FARSITE and BEHAVE allow managers to evaluate possible suppression tactics in order to more efficiently and economically suppress wildfires.

With technological advances, the development of GIS allows users to view spatial displays of landscape data. Raster-based themes, such as vegetation and terrain, may be overlaid with vector themes, such as boundaries and roads, as well as point data, such as buildings. The incorporation of this GIS technology into fire prediction allows fire managers to view potential fire behavior in relation to landscape data to more comprehensively identify risks and opportunities.

FARSITE, along with BEHAVE, the National Fire Danger Rating System (NFDRS), Wildland Fire Assessment System (WFAS), and the Fire Information Retrieval and Evaluation System (FIRES), has been incorporated into a comprehensive decision support system (DSS) for the fire risk assessment of prescribed fire management activities (Andrews and Williams 1998). This integration of various fire management tools provides managers with more complete information for decision making.

If used correctly, FARSITE can be an effective tool in the management of larger wildland fires (wildfires and WFURB). In order for this model to be used effectively, the user must have a full understanding of the assumptions upon which the model is based and the limitations to its successful application.

2.0 BACKGROUND

2.1 FARSITE DESCRIPTION

The FARSITE fire area simulator utilizes GIS capabilities, allowing the overlay of complex topography and fuels with barriers (e.g. rivers, roads, trails) and values at risk (e.g. developed areas and administrative boundaries) while simulating fire behavior under a variety weather conditions (Finney 1993; Finney 1995; Finney 1998). Version 1.0 was initially released in 1995 for use in the PC Windows environment. Continual improvement of this model has led to several subsequent versions, with the most recent version 3.0.9 released in March of 1999. The release of version 4.0, which will have several major changes, is expected out soon (Finney pers. com).

The FARSITE system is a compilation of several existing models based primarily on the BEHAVE system. The Rothermel (1972) surface fire spread equation, adjusted by Albini (1976), calculates the rate of spread of fire through the surface fuels as influenced by fuel bed characteristics, wind, and slope. FARSITE relies on the 13 fire behavior fuel models to describe fuel loading, fuel bed depth, and associated fire behavior (Anderson 1982).

VanWagner's (1977, 1993) crown fire model determines if and when a surface fire will make the transition to the crown fuels based on surface fire intensity and crown fuel characteristics. This model also determines whether a crown fire is characterized by active burning or independent crown fire, or simply by torching of individual trees (Finney 1998). Passive crown fire spread, under the assumption that spread is dependent on surface fire behavior, resorts back to Rothermel's (1972) surface fire spread model, while active crown fire spread is modeled using Rothermel's (1991a) crown fire model (Finney 1998).

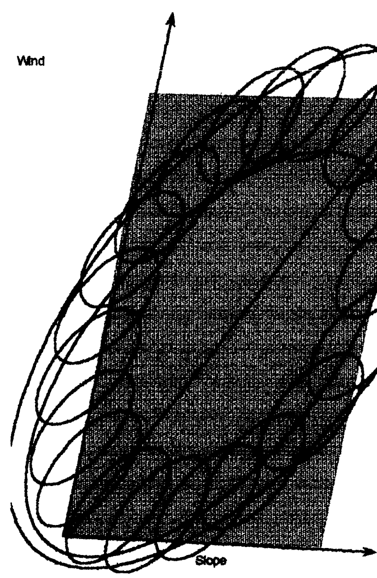
FARSITE uses Albini (1979) to determine spotting distance from torching trees, relying first on VanWagner (1977) for identifying conditions leading to torching trees. Although several models have been developed for spotting from various sources, including from wind-driven surface fires (Albini 1983), Albini's spotting from torching trees is the only model that currently adjusts for complex terrain (Chase 1981, Finney 1997). This spotting model calculates only the maximum distance embers may travel and ignite susceptible fuels. There is currently no method for calculating the number of embers or the possibility of embers landing on non-flammable material (rock or bare ground between fuels).

Fire behavior is simulated for a given time period and by a predetermined time step, to be defined by the user. The time step is the amount of time (e.g. 30 minutes or 2 hours) between each computation. All conditions are assumed to be constant during this period. It is preferable to use a shorter time step for faster moving fires to avoid losing detail, while longer time steps may be appropriate for slower moving fires to avoid unnecessary computations. Visible perimeters are produced at a predetermined visible time step, which may be less frequent than the time step for calculations. The distance resolution, which also may be selected by the user, is the maximum projected distance that cannot be exceeded within a time step before new fuels, weather, and topographic data must be reevaluated (Finney 1997). This should prevent the loss of too much detail in fire spread should conditions change rapidly.

An acceleration model (McAlpine and Wakimoto 1991) is included to account for the adjustment of fire behavior over time toward equilibrium rate of spread. Acceleration addresses the assumption that fire behavior does not spontaneously reach the new equilibrium rate of spread the instant conditions change. FARSITE also depends on the BEHAVE system model for calculating fuel moistures for the 1 and 10 hour fuels, and the National Fire Danger Rating System (NFDRS; Bradshaw et al. 1983) equations for calculating the 100 hour fuel moistures (Rothermel et al 1986).

Fire spread is modeled using Huygens' principal on wavelength propagation (Finney 1998, Finney 1997; Figure 2.1). Fire shape is assumed to be elliptical and the fire is broken down into a series of ignitions along the perimeter for calculations (Rothermel 1972). At each time step, points along the perimeter are used as starting points for computing fire spread for that time step and a new perimeter is subsequently drawn. The elliptical dimensions reflect the rate and direction of spread. The size (area and perimeter) of the ellipse is dependent on fuel, topography, and wind, whereas the shape (length to width ratio) is dependent on the slope and wind only (Finney 1998). The user may select a desired perimeter resolution so that as the perimeter expands, new points are automatically added to maintain resolution (Finney 1997). A greater density of points are desirable for a faster moving fire, while spatial conditions would change less frequently on a slower fire thus requiring fewer calculations to maintain resolution (S-493 class notes).

Figure 2.1. Huygen's elliptical fire growth (adapted from Finney 1998).



Recent versions of FARSITE also allow for the simulation of various suppression attack methods, including dozer or hand line construction and aerial retardant drops (Finney 1997). Information must be entered into the program, such as type of crew and rate of production. Studies addressing these production rates are listed in the User's Manual (Finney 1997) for reference.

FARSITE has been available since 1995 (version 1.0) and the use of this model has already been incorporated into the FBA repertoire. A new federal fire training course (S-493) was developed specifically for FARSITE application and operation (Finney and

Andrews 1999). The development and continual improvement of computer-based models such as BEHAVE, eventually replace older and outdated technologies like the TI-59 computer (Burgan 1979) or the HP-71B (Susott and Burgan 1986). At this point, however, FARSITE is not likely to replace the widely used, simple and versatile BEHAVE program (Andrews and Bevins 1998). Each program has its respective place in the FBA world, and each its limitations.

Although BEHAVE does not address complex topographical factors and fuels conditions simultaneously, nor does it translate fire behavior into spatial output, this program requires only minimal site-specific input and can be readily available for any area (Andrews and Chase 1990; Rothermel 1983). FARSITE, on the other hand, may address complex topography and fuels in a spatial setting, but its use is precluded by the intensive mapping effort, not to mention the computer expertise, necessary to set up the GIS layers (Keane et al 1998). This model was developed for long-range assessment of large fires, more specifically for the projection of PNFs in national parks and wilderness areas (Finney and Andrews 1999). It is not the most appropriate tool for evaluating fire behavior of small fires due to its coarse resolution. Nor would it be necessary to use this intensive system for areas with little variation in fuels or terrain, where the more simplistic approach of BEHAVE would be adequate.

2.2 APPLICATION of FARSITE

The FARSITE system has many potential applications in fire management, although it was initially developed for long-range projections of active PNFs (Finney 1995, Finney and Andrews 1999). Uses may range from assessing active fires to planning for potential fires or reconstructing past fire events. The 3-dimensional display of fire behavior on a landscape provides an effective visual tool for various educational and informative purposes.

FARSITE may assist in planning for wilderness fires (PNF, or WFURB), for example in locating an appropriate perimeter of a Maximum Manageable Area (MMA) or the development of alternatives for the Wildland Fire Situation analysis (WFSA). FARSITE may also assist in the planning of wildland fire management, such as identifying strategic placement of suppression resources and identifying potential resource protection needs. This may be useful in the early stages of a fire. Short-range (several hours) or mid-range (1-3 days) projections may help address questions about what the fire behavior "will" or" might" be under weather forecasted conditions (S-493). Long range assessment of fire behavior can incorporate FARSITE by simulating extreme case and more probable cases, using weather scenarios estimated from historical data to address "what if" questions (Rothermel 1994, Mutch 1994, Finney and Andrews 1999). FARSITE may aid in the assessment of PNF potential to escape the established MMA boundary, or the potential of a prescribed burn to escape control (Andrews and Williams 1998).

FARSITE may be used to reconstruct fire behavior of past fires or fire seasons. This may aid in evaluating past management actions or addressing policy concerns as well as setting up the validation of this system (Finney and Andrews 1999). Like previous models and fire behavior systems (e.g. Butler and Reynolds 1997; Anderson 1968), FARSITE may also be applied for research purposes to help better understand fire behavior on a complex landscape (S-493 Class Notes).

By evaluating potential fire behavior, FARSITE may be useful in locating areas with undesirable buildup of fuels. This can assist in planning efforts for fuels treatment. FARSITE allows for relatively timely evaluation of different fuels management actions through simulating potential fire behavior under various fuel conditions (vanWagtendonk 1996, Stephens 1998). Such evaluations can not be easily performed in real time field observations of actual treatments, which may take years or decades. Finney et al. (1997) used FARSITE, in conjunction with fuels treatment scenarios and suppression attack methods, to analyze cost-benefit of treating fuels. FARSITE may also be used in this manner to analyze various suppression alternatives (S-493 Class Notes).

FARSITE has been incorporated into larger ecosystem dynamics models to address fire in forest succession or disturbance modeling. For example, FIRE-BGC is an ecological process model for simulating fire succession on coniferous landscapes of the northern Rocky Mountains, which incorporates FARSITE along with many other dynamic landscape process models in an endless network of simulations (Keane et al 1996). Fire area, predicted by FARSITE, provides potential locations and frequencies for fire disturbance on the landscape. Fireline intensity, also predicted by FARSITE, provides for the interpretation of fire effects that would result in vegetation changes. For example, a low-intensity output from FARSITE would suggest occasional tree mortality and understory fuel consumption, thus altering the vegetation characteristics and dead organic biomass descriptions, which would consequently affect future fire intensities. While a stand-replacement fire would revert a given area back to the beginning of the succession model, FIRE-BGC likewise reverts back to the SEEDER model (Keane et al. 1996).

2.3 FARSITE DATA REQUIREMENTS

FARSITE requires a GIS landscape file (.LCP) containing database layers for elevation, slope, aspect, fuel model (as described by Anderson 1982), canopy cover (expressed either by percentage or by category), canopy height, crown base height, and crown bulk density. The last three themes, although optional, are necessary for crown fire modeling. Table 2.1 describes the usage of each of these landscape themes. All layers must be input at, or converted to, a 30 meter resolution for optimal use be FARSITE. This mapping process requires a commitment of time and money on behalf of the land management agency, and should be accomplished prior to the fire season (Keane et al. 1998).

Table 2.1 Raster inputs to FARSITE and their usage in the simulation. (Adapted from Finney 1998)

Raster theme	Units	Usage
Elevation	m, ft	Used for adiabatic adjustment of temperature and humidity from the reference elevation input with the weather stream.
Slope	Percent	Used for computing direct effects on fire spread, and along with Aspect, for determining the angle of incident solar radiation (along with latitude, date, and time of day) and transforming spread rates and directions from the surface to horizontal coordinates.
Aspect	Az	See slope.
Fuel model		Provides the physical description of the surface fuel complex that is used to determine surface fire behavior (see Anderson 1982). Included here are loadings (weight) by size class and dead or live categories, ratios of surface area to volume, and bulk depth.
Canopy cover	Percent	Used to determine an average shading of the surface fuels (Rothermel et al. 1986) that affects fuel moisture calculations. It also helps determine the wind reduction factor that decreases wind speed from the reference velocity of the input stream (6.1 m above the vegetation) to a level that affects the surface fire (Albini and Baughman 1979).
Crown height	m, ft	Affects the relative positioning of a logarithmic wind profile that is height extended above the terrain. Along with canopy cover, this influences the wind reduction factor (Albini and Baughman 1979), the starting position of embers lofted by torching trees, and the trajectory of embers descending through the wind profile (Albini 1979).
Crown base height	m, ft	Used along with the surface fire intensity and foliar moisture content height to determine the threshold for transition to crown fire (Alexander 1988; Van Wagner 1977).
Crown bulk density	kg m^{-3} lb ft^{-3}	Used to determine the threshold for achieving active crown fire density (Van Wagner 1977,1993).

FARSITE also requires continuous daily weather stream (.WTR) and wind stream (.WND) data for the analysis period. The weather stream contains daily high and low values for temperature and the times they occur, the high and low relative humidity (RH) values, daily precipitation amount, and the elevation at which these data were recorded. FARSITE then interpolates the temperature and RH throughout the day using a cosine relationship as described in Beck and Trevitt (1989). Temperature and RH are then used to calculate dead woody fuel moistures throughout the simulation (Finney 1997, 1998).

The model also uses the adiabatic lapse rate to estimate spatial variation in temperature and RH due to elevation changes (Finney 1998).

Initial fuel moisture values must be input into the model prior to the simulation. As the season progresses, however, these initial values are less important due to the weather-induced changes modeled over the course of that season, especially for the finer fuels that respond to environmental changes more quickly (Finney 1998). Fuel moisture values are calculated at hourly intervals (depending on the user-defined time step parameter) using the BEHAVE prediction system models for 1-hour and 10-hour time lag fuels (Rothermel et al .1986), and NFDRS models for the 100-hour fuels (Bradshaw et al. 1983). The fine fuel moisture calculations are computed differently at 1400 than for the rest of the hourly calculations, which may cause noticeable inconsistencies in fuel moistures (Finney 1997). These fuel moistures are then used to calculate fireline intensity, or the rate of energy release/unit length of fire front (Finney 1998).

The wind stream data, including wind speed, direction, and cloud cover, may include observations taken at various time intervals ranging from several hours down to the minute (Finney 1997). Although allows the user to input this information by the minute, wind data are not normally measured at this frequency and it is unrealistic to attempt to predict winds at this resolution. The user-defined time step parameter would override more detailed input data, and it is important to understand the limitations of one's computer system prior to changing parameters to increase the number of computations. Thus, wind inputs tend to be at a coarse temporal resolution, accounting for general shifts in the wind patterns only. These data may be input from weather forecasts, actual observations (*post facto*), or may be estimated from historical weather data for prediction purposes (Rothermel 1991b).

FARSITE can handle up to five separate weather streams and five wind streams at one time. Data from different locations (for example fire weather station, Remote Automated Weather Station or RAWS, meteorological stations, or spot weather observations) across the landscape can be collectively input to allow the model to approximate some spatial variation between the observations by extrapolation. This can be used to account for variations in wind patterns between ridgetops and valley bottoms (Finney and Ryan 1995) but only to the extent that these changes are captured in the data. FARSITE does not model terrain influences on wind (Finney 1998).

2.4 FARSITE OUTPUT

FARSITE simulations generate spatial output in the form of perimeters of potential area burned, along with tabular area and perimeter data for each time step. Perimeters may be saved as ASCII vector file, or ArcView shape file for visible time steps only or for all time steps. This output may then be imported into GIS for additional purposes. FARSITE also produces spatial data in raster form including time of arrival, fireline intensity, flame length, rate of spread, heat per unit area, crown/no crown, and spread direction (Finney 1997).

2.5 ASSUMPTIONS AND LIMITATIONS

Models, by nature, make simplifying assumptions about real-life events. The FARSITE model depends upon the various sets of assumptions required by each of the individual models. The overall effect may be compounded due to the possible interaction between these assumptions, possibly creating larger sources of error. It is also possible that multiple errors may mask the effect of the individual errors that may go unnoticed initially. This may lead to greater complications in the long run. It is important to maintain an understanding of these assumptions while analyzing FARSITE simulations in order to avoid making management decisions based on misinformation.

Surface Fire Behavior

Rothermel's (1972) surface fire spread model assumes the flame front to be advancing steadily, which follows along with the assumption that fuels are continuous and uniform for the scale at which they are input. Although realistically these condition rarely exist, resulting fire behavior may be "adjusted" to account for some of the variability within the spatial unit (e.g. 30m in FARSITE) for which this assumption applies (Finney 1998).

Currently, FARSITE only addresses spatially non-uniform conditions to the degree fuels and topography were mapped, with the smallest possible resolution being the 30-meter pixel. However, the user-defined time step and distance resolution must also be set low enough for that resolution to be maintained (Finney 1998). FARSITE does not allow for non-uniform fuel conditions within that resolution as described by Rothermel (1983) and Fujioka (1985) other than by a ROS adjustment factor (Finney 1998) or customization of a new fuel model. Rothermel (1983) and Brown (1982) suggest that a more realistic outcome may be obtained from calculating a weighted average ROS of two or more fuel models over a unit area, or a computed harmonic mean (Fujioka 1985), rather than to average all fuel characteristics prior to calculating ROS as suggested by Frandsen and Andrews (1979). This may be necessary for a variety of fuel types and conditions, for example in sagebrush or other shrub communities (Brown 1982). Although FARSITE does not currently incorporate any of these calculations, users may define custom fuel models to account for a mixture of fuels.

Fuel bed characteristics are classified as one of the 13 fire behavior fuel models described by Anderson (1982) or by the customization of fuel model based on the same principles (Finney 1997). These fuel models were developed for the relative ease of describing fuels in regard to vegetation and expected fire behavior, in a timely manner while avoiding unnecessary detail. Their use, however, requires generalizations to be made (Anderson 1982).

FARSITE can handle multiple fires simultaneously, but does not account for the interaction between these fires. Perimeter crossovers and merging fires are processed simply to remove illogical vectors. There is no distinction between burned and unburned areas within the perimeters (Finney 1998). It is assumed that fire acceleration toward the equilibrium rate of spread is not influenced by fire behavior itself. Fire spread is assumed to be independent of the shape of the fire front (Finney 1997) even though this is an understood phenomenon. For example, in prescribed burning various ignition patterns may be utilized in order to achieve desired fire behavior.

Fire spread is assumed to be in the shape of an ellipse. Although there are several variations, such as the double ellipse, the oval, or egg-shape, the ellipse has been shown to apply on simple landscapes (Green et al. 1983). It is unknown at this time how this shape applies to the complex landscapes used by FARSITE (Finney 1998), but facilitates the mathematical computations used for fire spread.

Wind and Weather Input

Winds are assumed to remain constant on the temporal and spatial scale at which they are input. FARSITE does not modify the direction of winds for topographical features, such as canyons and steep slopes (Finney 1998). This variability must be handled manually if considered to be an influencing factor. The location where this data was collected is an important factor in capturing some of the spatial variation. Distance between the weather stations and the fire may greatly affect accuracy of the data.

The wind stream data may input down to the minute. It is impractical however, to input a wind stream this detailed, since wind data are not recorded this frequently. A minute is still a very coarse resolution for wind patterns. For example, 10-20 second gusts every few minutes may be a critical factor in driving fire spread, but may escape detection by existing recording devices. Due to the complex variability of temporal wind patterns, it is beyond the scope of this model to attempt to predict these patterns at this time.

Therefore, it is best to input only general wind patterns across the landscape and assume that a constant wind speed will capture most of the variation between the gusts and calms.

FARSITE makes the assumption that the elliptical dimensions of fire spread are not influenced by fluctuations in wind speed and direction at a greater frequency than that input into the model, although fine resolution wind patterns are known to influence fire spread. Wind is a major factor contributing to fire spread and it may be appropriate under certain fuels and weather conditions to use maximum wind speeds or average gust speeds rather than the 10-minute average recorded by weather stations (Finney 2000).

Although winds may be input at a finer resolution than the typical hourly observations, modern computer capabilities become the limiting factor to obtaining results in a timely manner. Despite increases in memory and speed, the newest PCs become bogged down with additional calculations of all parameters at the finest resolutions possible. The user must make some necessary generalizations by setting the appropriate time step for calculations. Adjustment factors may be used to calibrate a more appropriate rate of spread, accounting for variation in wind speed (Finney 1997).

The weather stream parameters (temperature, relative humidity, and precipitation) are also assumed to be steady. Although these parameters do fluctuate temporally, they do so to a much lesser degree than wind. Temperature and RH are critical in the fuel moisture calculations where they are lumped into groupings of several degrees or percentages

(Rothermel 1983). Slight fluctuations in these parameters, therefore, should result in only in a slight, if noticeable, error in fire behavior predictions.

Because only the daily high and low values of temperature and RH are input, fire behavior calculations must depend on the assumption of steady change of these parameters by a cosine curve relationship between the two extremes. Also, the occurrence of the RH extremes are not timed, but assumed to coincide with the temperature extremes (Finney 1997). It is possible that a lag in the humidity response to temperature would result in 1) high temperature coincident with an RH above the low value, and 2) low RH coincident with a temperature below than the high value. Either scenario may result in fire behavior slightly less than that predicted under this assumption. As stated before, however, this error may be unnoticeable.

In using the adiabatic lapse rate to approximate spatial variation in temperature and RH due to elevation changes, FARSITE assumes good atmospheric mixing with no inversions (Finney 1998). The more complex the landscape, however, the greater the opportunity for the occurrence of inversions. Inversions are a real concern in fire behavior as nighttime temperature and RH recovery may be greatly affected, and these localized conditions are often not recorded at the weather stations. Unless this weather pattern is captured by the weather stations, fire managers (fire behavior analysts) must account for this phenomenon outside the realm of FARSITE.

Precipitation is assumed to be constant across the landscape (Finney 1998) and since it is recorded at 24-hour intervals, other factors such as type of precipitation and intensity are assumed not to be contributing factors. It may be important to obtain local precipitation via spot weather forecasts and/or local fire weather observations to capture a more realistic picture.

The ability to predict weather is a major limitation in the use of any fire behavior model for predicting future fire behavior (Rothermel 1991b, 1994). Short-range (1-3 days) weather forecasts may be highly accurate at the local level, while mid-range (3-5 days) forecasts tend to retain a high level of accuracy but are more general in temporal and spatial scales. Extended-range (10-30 days) weather forecasts contain much more general information on large scale atmospheric conditions (Fosberg 1987). Although FARSITE is a good tool for long-term fire planning, these limitations prevent us from obtaining accurate long-range predictions. It is virtually impossible to predict specific weather events or sequence of events, such as the passing of a dry cold front, far into the future. The timing of such weather events may be critical, as the resulting fire behavior would depend on size and location of the fire at the specific time (Finney, per. comm.).

General weather scenarios may be estimated using historical data, but this may be limited by the availability of such data. Again, due to the remote nature of many of the areas in question, we are limited to the amount of data available (often limited to the past 20 or 30 years; Rothermel 1991b). This may provide adequate data to estimate mean values, but will rarely capture the possible extremes, especially in wind patterns such as those observed in Yellowstone in 1988 (Rothermel 1991b). This does not allow for the full range of possibilities, especially in determining extreme case scenarios, which may be a 100-300 year event.

The source of weather data can also be limiting. For instance, different types of weather stations may collect observations at different times or frequencies throughout the day. This may be important especially in capturing some of the temporal variation in the winds. However, wind data, even at the 1-minute scale, may still be too general and it is unrealistic at this time to expect more detailed observations (Finney, personal comm.). Also, the distance between the location where this data was collected and the fire is an important factor in capturing some of the spatial variation.

Crown Fire Modeling

Crown fire modeling assumes that crown fuels are uniform at the scale to which they are input. Crown fire behavior is only based on 1, 10, and 100-hour fuels. Potential for crown fire may be underestimated under the assumption that 1000-hour fuels do not contribute (Finney 1997). Crown fire simulation also uses the wind-slope vector direction from the understory surface fire with mid-flame winds (Finney 1998). This may be inappropriate since these vectors are highly dependent on surface fuel bed characteristics, which are several meters below the crown.

Spotting from Torching Trees

Albini's (1979) equation for spotting from torching trees is currently the only spotting model applicable to the complex topography found in FARSITE. FARSITE does not address spotting from running crown fires or surface fires because these models were developed for flat terrain and do not account for complex phenomena such as firebrands crossing narrow ravines. Under Albini's equation, FARSITE does not predict the number of embers produced, or the exact locations where they may land. Only the direction and distance embers may travel are modeled. FARSITE does allow the user to adjust the percentage of successful embers that result in spot ignitions. This addresses the possibility that many of the tiny embers may not fall directly on fuels, but rather in the spaces between, or that these embers may not be significant enough to actually ignite the fuels (Finney 1998).

This spotting model also assumes that wind speed varies only as a function of height above ground and flow parallel to the ground. As a result ember size, lofting height, and the ultimate spotting distance of running crown fires may be underestimated (Finney 1997). Ember particle shape is assumed to always be cylindrical, with only the particle size variable. This implies that the "drag coefficient" and specific gravity are constant for all embers (Finney 1998).

Attack Menu

Using the attack methods options, FARSITE assumes that line construction is adequate to contain that portion of the fire. Direct and indirect line are assumed to be impermeable to surface and crown fire spread. However, torching near the fire line may allow spots across these barriers (Finney 1997). FARSITE does allow for a temporal shift in the effectiveness of aerial retardant drops as the retardant has the opportunity to dry out over time. However, it does not account for the probability of ineffective placement of the aerial drops, which occurs frequently due to strong winds or poor visibility.

Mapping Limitations

The mapping process requires a time and money commitment, both of which are limiting factors to most land management agencies (Keane et al. 1998). Accuracy of this mapping requires the proper use of approved methods by skilled professionals and extensive ground truthing for verification. Much of the land area ideal for the use of FARSITE exists in remote Wilderness and National Park areas, which tend to be in higher elevations with complex topography. Ground truthing of these remote areas is limiting both logistically and financially (Keane et al. 1998). Actual verification plots may be concentrated in more accessible terrain and may bias results. Consistency is another concern in mapping, especially across agency boundaries where variations in methodology or sampling intensities may have been used (Roy Renkin pers. comm.). Ideally, a system should be developed that would be universal to all agencies and relatively simple for users of varying backgrounds. This may however be impractical due to regional variations in vegetation/fuels, and thus mapping procedures.

Some of the parameters may be very difficult to measure in the field. For example, understory vegetation characteristics are difficult to measure through the canopy using satellite imagery (Keane et al. 1998). Crown characteristics such as crown bulk density may be estimated using previous extensive studies to avoid complicated field measurements (Brown, et al. 1977, Keane et al. 1998) and crown base height is subject to much complication (VanWagner 1993). Lumping fuel types into the 13 fire behavior fuel models may at times be inadequate. FARSITE does allow for the creation of custom fuel models or the conversion of existing fuel models. Fuel models may also be changed manually when necessary (Finney 1997, 1998). For instance, live fuel moistures may drop throughout the season to a level where the combustion of live foliage alters the fire behavior to fit a different fuel model. FARSITE assumes that live fuel moistures remain constant throughout the simulation, so this must be accounted for manually outside of FARSITE if necessary (Finney 1997).

Rate of Spread Adjustment Factor

Rothermel's fire spread equations, as used in FARSITE, continually overestimates fire spread (Cruz 1999, Finney 1997, Rothermel 1972) due primarily to the combination of previously stated assumptions and limitations. FARSITE does allow for the calibration of each fuel model using an adjustment factor, which is multiplied times the rate of spread (ROS) to achieve a more realistic outcome. This adjustment factor method is an oversimplified quick fix, assuming a simple linear relationship between all errors and ROS, and may be specific only to the given conditions.

At any one time, due to errors inherent in this complex model, multiple errors may be present. These errors may compound each other, or may mask each other. Since the correct answer is the desired result, the method used to achieve it may still be acceptable despite these errors. However, an adjustment factor may not apply to another fire in the same area under even slightly different conditions. The adjustment factor may even need to be manually changed for a fuel model during a single simulation (Finney 1997). For instance, the passage of a cold front may alter conditions such that the initial adjustment factor is no longer appropriate.

Other Limitations

FARSITE does not predict whether an ignition will burn or not. This model assumes that an ignition source will lead to fire spread. This model does not currently address large fuel burnout or fire spread by smoldering combustion or rolling debris. "Holdover" fires may remain inactive for a periods of time yet sustain heat through smoldering combustion. This phenomenon, which is common in fuel types with deep duff or a heavy large diameter fuel component (Sellers and Despain 1976; Williams and Rothermel 1992), can not be addressed by current fire behavior models.

Current fire behavior models do not address the occurrence of inversions, and their influence on fire behavior. Inversions are a common occurrence in mountainous terrain, where pockets of cool air are trapped in valley bottoms by warm pockets of air above. These warm pockets may lie at mid slope, creating a thermal belt in which fires may remain very active throughout the nighttime. Normally, fires tend to remain inactive during most of the night and into the morning due to the lower temperatures and higher humidities. Inversions may not lift until mid to late morning, thus delaying the increase in fire activity. Fire behavior models assume diurnal fluctuations in temperature and humidity are continuously changing between the recorded highs and lows.

FARSITE does not predict where fire may cross a barrier, and assumes that barriers are impermeable to surface fire and crown fire spread. Fires may penetrate a barrier by spotting only. Some barriers that affect actual fire spread may not show up at the 30-meter resolution. Barriers, such as rivers and roads, will need to be input into FARSITE separately (Finney 1997). The user must ensure that important barriers are wide enough to be detectable by FARSITE by adjusting model parameters. The distance resolution is the maximum distance the fire may spread until FARSITE is required to reevaluate spatial data.

Although FARSITE involves 3-dimensional data as input through GIS, the fire models were developed for simple landscapes, with fire spread calculated from a 1-dimensional point and projected into a 2-dimensional fire front (Finney 1998). This leaves many complex questions that still need to be addressed.

2.6 FARSITE VALIDATION

FARSITE validation depends largely upon the performance of all the individual models, as well as the accuracy of the input data and the appropriate use of this system. It is important to prioritize the problems in order to proceed with validation. The appropriate sequence should address data error or inadequacies first, followed by user error, and then model limitations can be assessed (S-493 Class Notes). The inadequacy of the input data overrides the performance of the model.

FARSITE was initially tested by simulating fire behavior of PNFs in Sequoia National Park (Finney 1993). Additional model testing was performed during the course of the 1994 and 1995 fire seasons in Yosemite National Park (Finney and Ryan 1995, vanWagtendonk 1998), and during the 1994 fire season in Glacier National Park (Finney and Andrews 1994). PNFs provide a unique opportunity to study fire behavior on a complex landscape, where a wide range of temporal and spatial variations in fire behavior parameters influence the dynamic process of fire spread (Finney and Andrews 1994).

Validation exercises have recently been performed on two historic fires in the Boundary Waters Canoe Area preliminary to an analysis of fire potential due to the recent blowdown event (Finney 2000). Many other validation and calibration exercises have been performed in various forest and park areas for local use, but results are rarely published (Finney pers. comm., McHugh pers. comm.).

3.0 STUDY AREA

Yellowstone National Park encompasses over 2.2 million acres situated in the northern Rocky Mountain region of northwestern Wyoming, extending slightly into southwestern Montana and southeastern Idaho. Terrain consists primarily of high volcanic plateaus in the central and southwest portions of the park surrounded by the steep slopes of the Rocky Mountains to the east and north. Elevation ranges from 5,265 feet near the north entrance to 10,000 and 11,000 feet mountain peaks. The majority of the park lies in the subalpine zone between 7,000 and 9,000 ft (Despain 1990).

3.1 CLIMATE

Topography in conjunction with predominant air flow have been identified as major climatic influences for the Yellowstone region, resulting in two major climates in YNP (Despain 1990, 1987). Snowfall accounts for most of the annual precipitation in mountainous areas. The valley areas and central plateau region, which receive more of the precipitation as spring rains, tend to be caught in the rain shadows of the continental divide to the southwest and the Absaroka Range to the northeast (Despain 1990). Annual precipitation varies from 10-12" near the north entrance to a maximum of 70" in the southwest corner. Much of the park receives 30-50" depending upon elevation (Despain 1990).

3.2 VEGETATION

Mountain slopes as well as the central plateau region tend to be covered with coniferous forests. Mountain valleys, including areas in the northern portion of the park along the

Yellowstone and Lamar River valleys are primarily non-forest vegetation (big sagebrush and dry grasslands), with Douglas-fir growing on north facing slopes. Lodgepole pine communities predominate in areas where coarse rhyolitic soils occur (Despain 1990).

Forest cover types have been classified by Despain (1990) by species and structure. LP0 refers to early successional stands of lodgepole pine from recently burned to 40 years old. LP1 refers to young stands of lodgepole between 40 and 150 years old. LP2 refers to 150-300 year-old lodgepole stands with development of a spruce/fir understory, and LP3 refers to 300+ year old dense stands of pine, spruce and fir of all ages with accumulation of dead fuels. LPP refers to climax (300+ year old) stages of lodgepole pine, with young lodgepole pine in the understory, that occur primarily in areas with dry rhyolitic soils (YNP 1992, Romme and Despain 1989). A similar classification is described for Douglas-fir (DF0, DF1, etc.) whitebark pine (WB0, WB1, etc.), and spruce fir (SF0…). Aspen, limber pine and less common mixed forest types, as well as non-forest cover, primarily grass and sagebrush, are also present (YNP 1992).

3.3 FUELS

These cover types can be converted to NFFL fuel model (Anderson 1982) based on the fuel characteristics associated with the forest age structure and observations from past fire behavior. Non-forest cover types can also be converted based on vegetation characteristics and expected fire behavior. For this study, NFFL fuel model 1 is used to define fuels and fire behavior associated with open grasslands, such as cheatgrass and fescues. Fuel model 2 refers to grasslands with greater fine fuel loading, including a sagebrush component, as well as open Douglas-fir (non-forest) stands, in which grasses and some timber litter carry the surface fire. Fire spread in fuel model 2 tends to be slower than that in fuel model 1, but with greater intensities due to greater fuel loadings. Sparse distribution of fuel model 3 occurs only in the Gardner River drainage and along the western edge of the park depict non-native tall grasses which experience the highest rates of spread and intensities of all grass models.

Fuel model 5 is used frequently to describe various shrub communities, except for sagebrush, as well as moist areas and mid-successional aspen stands. Due to its slow rate of spread, fuel model 5 is also used here to describe recently burned stands (as interpreted from the 1988 Burned Area Survey) in which light surface loadings of grasses, forbs, and shrub litter. Fuel model 8 refers to early stage Douglas-fir, LP1, and LP2 stands, and fuel model 10 for the later stage Douglas-fir and LP3 stands (YNP 1992, Sorbel 1998, Renkin, pers. comm.). Both of these fuel models experience surface fire spread through the timber litter, but greater fuel loadings including a large diameter dead fuel component creates significantly greater fire spread and intensities in fuel model 10. Fire behavior in the more decadent stands of FM 10 experiences frequent torching, due to surface fire intensities and ladder fuels, with fire spreading via spotting and occasional crown fire.

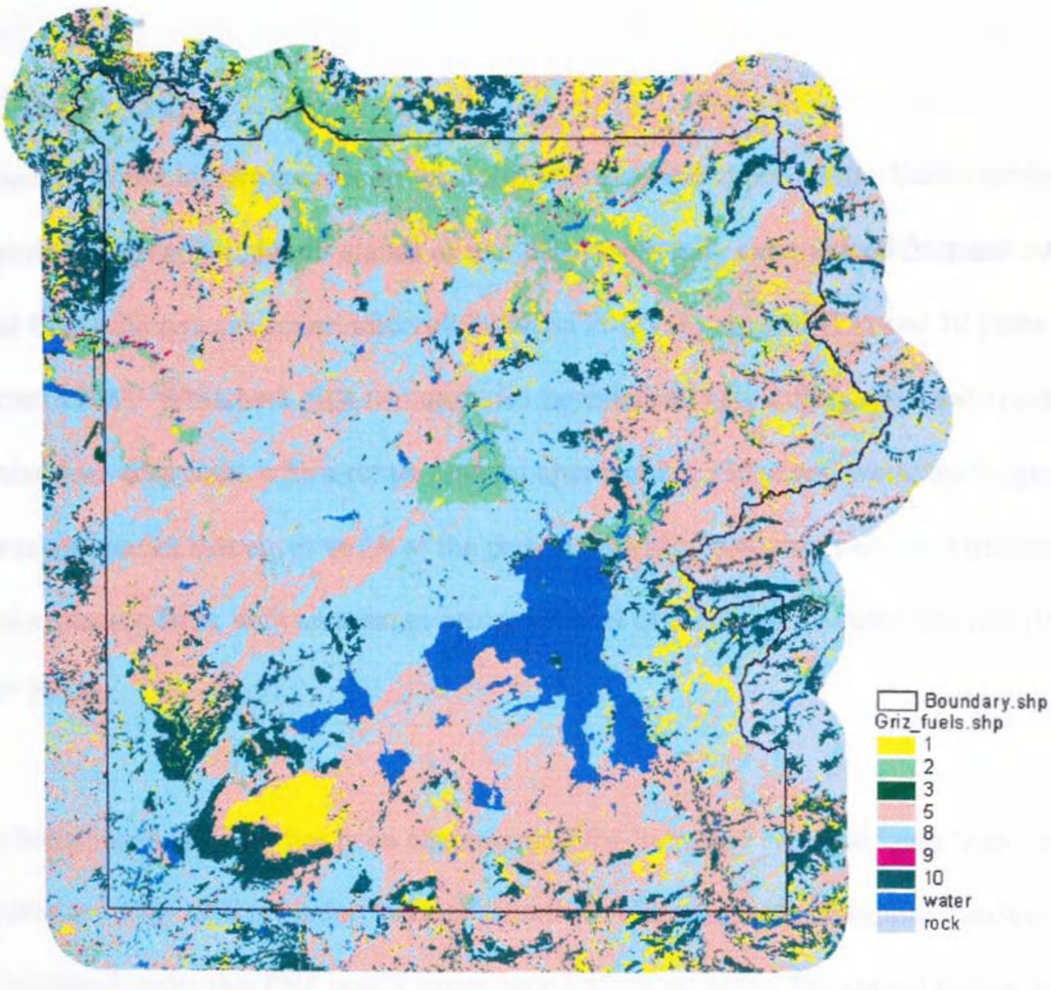


Figure 3.1 Fuel model distribution across the Yellowstone landscape, with a 5-mile buffer.

Infrequent occurrences of climax aspen stands are depicted by fuel model 9, which experiences a spread rate approaching that of fuel model 10, but with lower intensities. Refer to Anderson (1982) for full descriptions of the NFFL Fuel Models and associated fire behavior characteristics.

3.4 FIRE IN YNP

According to fire history studies on the northern range and upper Lamar Valley areas of the park, the open Douglas-fir stands of this area historically experienced frequent non-lethal fires with average return intervals between 20-25 (Houston 1973) and 30 years (Barrett 1994). Whitebark pine communities experienced very infrequent stand-replacing or mixed-severity fires, with a return interval approaching 350 years, while the lodgepole pine communities that cover much of the park historically have experienced infrequent stand-replacing fires, with an average return interval of 200 or more years (Barrett 1994; YNP 1992).

Fire behavior in the YNP has been characterized for "normal," "intense," and "extreme" conditions (YNP 1992). Under "normal" conditions, the majority of lightning strikes that are managed under this PNF policy experience little or no active fire spread before they are naturally extinguished (Varley 1993, Renkin and Despain 1992, YNP 1992; see Table 3.1). Since the "extreme" fire behavior experienced in 1988, only the 1994 and 1996 fire seasons have experienced conditions "intense" enough for wildfires and designated PNFs to burn actively. Prior years of intense fire activity include 1979, 1981, and to a lesser extent 1987 (see Table 3.1). Large fire activity from these two recent seasons is the subject of this study.

Thousand-hour fuel moisture is an indicator of drought severity or periods of high fire danger (Peterson 1988; Bradshaw et al. 1983). In Yellowstone NP, large fire activity has been observed to increase as these 1000-hr fuel moisture index values approach 13% (see Figure 3.2; Renkin and Despain 1992). Data from the Mt. Sheridan weather station has been used to examine those relationships and is representative of seasonal weather patterns for the alpine regions of the park (Renkin and Despain 1992; Renkin pers. comm.). Mammoth weather station data has also been included due to its closer proximity to some of the study fires, which occurred in the lower elevation climate of the northern range (Despain 1990).

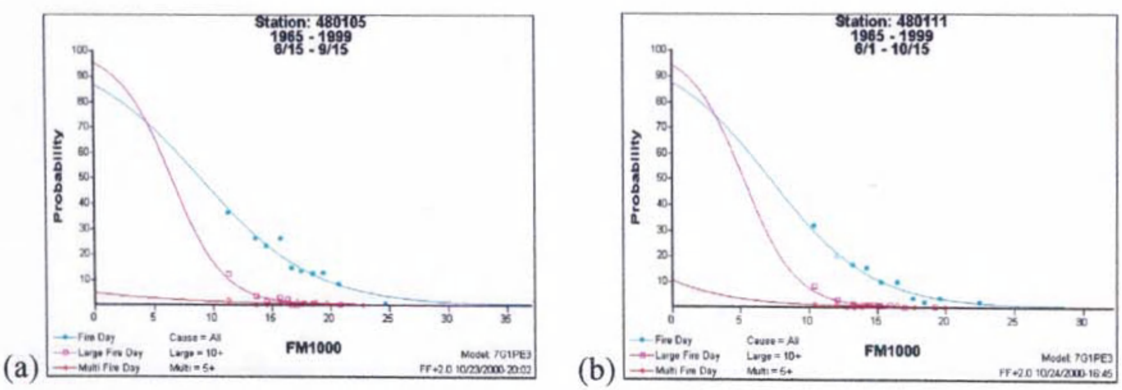


Figure 3.2 Probability of fire days, large fire days, and multiple fire days by thousand hour fuel moistures from (a) Mt. Sheridan and (b) Mammoth weather stations (NFDRS fuel model G) for the period of June 1 through October 15, 1965-1999 (adapted from Fire Family Plus; USDA For. Serv. 2000).

Little information is available on the frequency or conditions contributing to the occurrence of "holdover" or "sleeper" fires. While fuel moisture remains too high for active fire spread, conditions allow for smoldering combustion to sustain heat over a period of days or even weeks (Renkin and Despain 1992; Sellers and Despain 1976). After a warm, dry spell, fuel moistures may eventually drop low enough for these fires to become active.

The Energy Release Component (ERC), which reflects seasonal trends in drying and wetting of fuels, has been identified as a good indicator of fire danger in YNP (Andrews and Bradshaw 1996). ERC, which describes the total energy released per unit area during flaming combustion (Bradshaw et al. 1983; Deeming et al. 1977), is derived from live and dead fuel moistures (weighted toward the larger diameter fuels). The higher the ERC value, the higher the probability of large fire, with an increasing chance of large fire growth above ERC of 50 (see Figure 3.3).

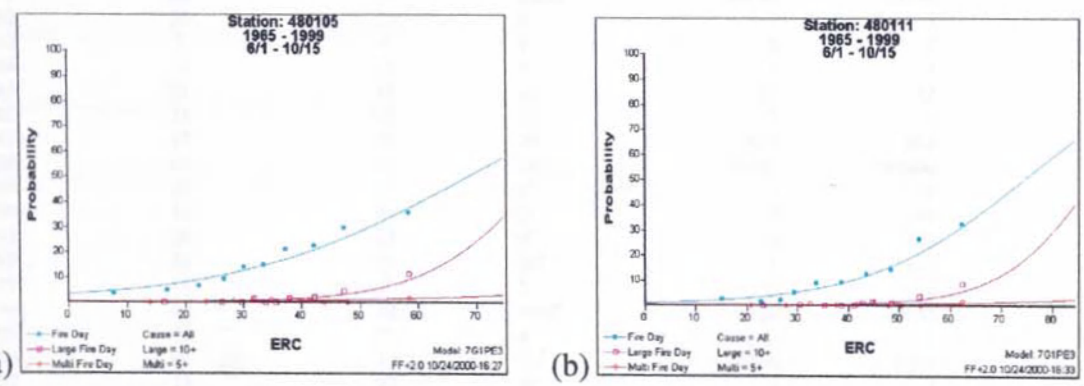


Figure 3.3 Probability curves for fire days, large fire days, and multiple fire days by Energy Release Component (ERC) from (a) Mt. Sheridan and (b) Mammoth weather stations for the period June 1 through Oct. 15, 1965-1999 (Adapted from Fire Family Plus; USDA For. Serv. 2000).

3.5 FIRE MANAGEMENT IN YNP

The first 100 years of YNP management focussed completely on fire suppression. As information and attitudes changed, due in part to the 1963 Leopold Report, National Park

Service policy began to change by accepting the role of fire in natural park areas. By 1972, YNP adopted its own Prescribed Natural Fire policy (YNP 1992). Since then, many fires had been allowed to burn naturally with little or no influence by human activities. Recent attempts to universalize terminology across agency boundaries have resulted in the new term "Wildland Fire Use for Resource Benefit" or WFURB" (USDA/USDI 1998). Table 3.1 summarizes the annual fire activity in YNP under the PNF/WFURB program, 1972 to 1999.

Table 3.1. Yellowstone National Park fire season summary, 1972-1999 (adapted from Renkin and Despain 1992, with additional data from YNP fire management records).

Year	Total number of fires	Number of lightning-caused fires	Number of PNFs	PNF Acres	Total acres burned	% normal precipitation[a]
1972	21	15	4	3	5	155
1973	33	24	2	3	146	103
1974	38	28	7	830	1307	60
1975	26	18	9	3	5	75
1976	30	19	15	1552	1604	166
1977	29	18	8	10	165	119
1978	24	12	6	5	15	65
1979	54	29	18(4)	10519	11233	73
1980	25	21	16	3	5	122
1981	64	57	28(2)	20240	20596	77
1982	20	13	9	3	3	118
1983	7	4	4	3	3	137
1984	11	11	9	3	3	138
1985	53	43	42	32	32	90
1986	33	27	27	3	3	114
1987	35	29	29	959	964	117
1988	45	39	29(14)	N/A[b]	793866	32
1989	24	17	0[c]	0	11	79
1990	42	36	0[c]	0	248	61
1991	28	23	0[c]	0	267	63
1992	30	27	16[d]	4	487	133
1993	10	7	5	1	1	112
1994	64	38	4 +2[e]	7728	16352	89
1995	16	10	9	2	3	102
1996	24	19	13[f]	3260	3264	48
1997	13	12	11	1	1	156
1998	13	13	11	108	124	117
1999	15	11	10	1	4	82
Total	827	620	312(20) + 2	45273	850717	2802
Average	30	22	11	1617	30383	100

[a]Precipitation averages were based on 30-year period, 1950-1980 for years 1972-1989, and 30-year period 1961-1990 for years 1990-1999
[b]Data not available to differentiate areas burned, while fire complexes were managed, as prescribed natural versus suppression entries
[c]All fires were suppressed pending approval of the new fire Management Plan in 1992
[d]Suppression actions initiated on 1 fire after exceeding management prescriptions
[e]Two fires were suppressed under confine/contain strategy, but major portions were allowed to burn
[f]One fire in was converted to a wildfire and suppression actions taken

The park's fire management plan, revised once in 1976 to include a larger area in the "natural fire zone," remained unchanged until the events of 1988. Much was learned about fire behavior and fire management from that extreme fire season. The YNP fire management plan as well as all PNF plans nationwide were suspended awaiting a national fire management policy review. Subsequent major revisions led to the current plan.

The YNP Fire Management Plan (1992) described 3 Fire management zones within the park. The Prescribed Natural Fire Zone covers the majority of the park where a lightning-caused fire could be allowed to burn provided it continually meets prescription. The Conditional Zone consists of the area within 1.5 miles of the park boundary as well as large drainages in which fire would pose a greater threat to the boundary. PNF management within this area is allowed under prescription provided either suppression actions are taken to prevent spread of the fire onto the adjacent forest or that forest has agreed to accept the fire. The Suppression Zone includes a 1/4-1/2 mile buffer around all developed areas in which no PNF activity is acceptable.

4.0 METHODS

4.1 GIS LANDSCAPE FILE (.LCP)

All GIS data layers required to build the FARSITE landscape (.LCP) file, including slope, aspect, elevation, fuel model and all crown characteristics, were created by park GIS specialists prior to the implementation of this project (Sorbel 1998).

Elevation, Slope, and Aspect

GIS themes for elevation, slope, and aspect were derived from the park's 10-meter digital elevation model (DEM) with a five-mile buffer around the park to allow for fires near the boundary crossing into other administrative units. DEM data for areas outside the park were obtained from the Geographic Information and Analysis Center at Montana State University in Bozeman. These layers were then converted into the 30-meter grid for FARSITE use (Sorbel 1998).

Vegetation/Fuels

An ongoing effort for grizzly bear recovery in the GYA has involved spatial data gathering for cumulative effects modeling. Much of this data is consistent with the needs of the FARSITE program and attempts have been made to use this existing data to avoid added expense and time.

The mapping efforts were accomplished over several years and at various resolutions. The original mapping effort, initiated in the early 1970s, inventoried forested Habitat

Type, as described by Pfister et al. (1977) and Steele et al. (1983), and non-forested habitat within YNP at a minimum resolution of 30 acres (Mattson and Despain 1985, Dixon 1997). Subsequent mapping efforts inventoried existing vegetation cover type (Mattson and Despain 1985) at a 5 acre resolution, which was overlaid with the Habitat Type map for more complete vegetation and site analysis (Dixon 1997). After the fires of 1988, this map was updated at a 50-meter resolution to incorporate changes in cover type due to burn severity, as surveyed by Despain et al. (1989).

Additional work has recently been accomplished to update this map to incorporate the decade of fire activity since 1988 (Sorbel 2000). During this time, over 20,000 acres burned within park boundaries (YNP fire management records) altering vegetative and fuel conditions. This work was not incorporated into the map used in this study since it alters fuel conditions in the areas burned by the 1994 and 1996 fires. Mapping efforts for forest units adjacent to the park, initiated in the 1980s, involved mapping both Habitat Type and cover type at the 5-acre resolution and have not been updated to include large scale fire disturbance (Dixon 1997).

The existing cover type values, including 38 forest and 40 non-forest cover types, were converted into fire behavior fuel models, as described by Anderson (1982), and input into a separate GIS layer. Cover types were used to delineate timber fuel models, while Habitat Types were used for non-forest areas to delineate non-forest fuel models (Sorbel 1988). The resulting fuel map includes 7 fuel models (1, 2, 3, 5, 8, 9, and 10), water, and rock (Figure 3.1). The basic cover types and fuel model conversions are defined in

Table 4.1. Forested cover type, as described by Despain (1990 and 1977), and non-forest cover type conversions were developed by Renkin (pers. comm) as shown in Table 4.2.

Table 4.1. Conversion of forest cover type to fuel model

Cover type	Stand description	Fuel Model
df0	post-disturbance Douglas-fir	1
df1	early successional Douglas-fir	8
df2	mid-successional Douglas-fir	8
df3	late-successional Douglas-fir	8
df	climax stage Douglas-fir	8
lp0	post-disturbance lodgepole pine, 0-40 years	5
lp1	50-150 year old even-aged lodgepole pine	8
lp2	150-300 year old lodgepole, with some spruce/fir saplings	8
lp3	>300 year old lodgepole, spruce/fir understory	10
lp	climax lodgepole pine, no spruce/fir	8
sf0	post-disturbance spruce/fir	1
sf1	early successional spruce/fir	8
sf2	mid successional spruce/fir	8
sf	climax Engleman spruce and subalpine fir	10
wb0	post disturbance whitebark pine	1
wb1	early successional whitebark pine	8
wb2	mid-successional whitebark pine	8
wb3	late-successional whitebark pine	10
wb	climax stage whitebark pine	8
lpp	pygmy lodgepole pine	8
kh	Krummholz	2
asp0	post-disturbance aspen	2
asp1	early successional aspen	2
asp2	mid-successional aspen	5
asp3	late successional aspen	8
asp	climax aspen	9

Table 4.2. Conversion of non-forest cover types to fuel model

Description	Fuel Model
Low Tall Shrub Comm	5
Moist Sage/ Cinquefoil	2
Dry Sage	2
Low Willow	5
Rocky Moist Sage	1
Forb Seep	5
Wet Forb Meadow	5
Moist Forb Meadow	5
Dry Forb Meadow	1
Low Marsh/Fen	98
Low Wet Grassland	5
Low Moist Grassland	1
High Rocky Grassland	1
Dry Grassland	1
Wet Opening	5
Moist / Dry Opening	5
Tundra	99
Exposed Bedrock	99
Talus	99
Stream Course	98
Standing Water	98
Cliffs	99
Shrub Avalanche Chute	99
Gram / Forb Avalanche Chute	99

The 1996 Coyote PNF crossed jurisdictional boundaries onto the Gallatin National Forest, requiring the necessary data base layers to be incorporated into this study to analyze this fire. A five-mile buffer around the park was included for this effort to allow for fires near the park boundary crossing jurisdictional lines. Due to the collaborative mapping effort for grizzly bear recovery in the greater Yellowstone area (GYA), GIS vegetation data layers already exist for much of the national forest areas adjacent to the park in a similar format, with slight variation as described by Dixon (1997).

Abrupt changes in fuel models at the park boundary became apparent, as the various data collected by the different agencies were placed side-by-side. Some of these changes may be explained by topographical features that may have served as appropriate boundaries (e.g. ridgetops or valley bottoms) or by variations in vegetation management on the opposing sides of the jurisdictional line (e.g. logging practices). Some of the discrepancies may also be due to mapping limitations or by variations in the methods used by the different agencies. This mapping effort was not focussed exclusively on producing fuel models for fire behavior analysis, and important fuel characteristics such as small fuel breaks and discontinuity of ground fuels, may not have been captured.

Although the updated map has been converted into the required 30-meter grid for FARSITE use, it is important to note that this is not the true resolution of the data, which is still limited primarily to the 5-acre resolution of the original cover type data.

Canopy Cover

The fifth spatial data layer required by FARSITE is that of canopy cover. This was estimated based on cover type (Tables 4.1 and 4.2). For ease of making broad-based estimations, percent canopy was generalized into 4 broad classification groups (Table 4.3). For all cells with two or more cover type values, canopy class for each cover type were averaged together (Sorbel 1998). All records that could be characterized as non-forest were assigned a canopy class of 0. All records that could be classified as forest/non-forest mosaics were given a canopy class of 1.

Table 4.3. Canopy cover classification.

Canopy class	% canopy cover
1	0-25
2	26-50
3	51 – 75
4	76-100

Although the vegetative mapping has been completed for the Grizzly Bear Recovery Area (see Dixon 1997 for delineated area), much of the national forest area outside this zone has not yet been mapped. The process, however, has been established (Dixon 1997; Mattson and Despain, 1985). Completion of this vegetation mapping, and subsequent conversion to the necessary fuels database, will facilitate the use of FARSITE for interagency fire planning efforts within the GYA.

Canopy Characteristics

Three additional spatial data layers were input into FARSITE for the modeling of crown fire and spotting. Crown height, crown base height, and crown bulk density were estimated from the vegetation map with the assistance of field sampling (Sorbel 1998). Crown characteristics were assigned to all forested, non-forested, and mixed forest cover types in both the Despain cover type map of Yellowstone National Park, and the Grizzly Bear Habitat Component map of the GYA with a five-mile buffer around YNP. These estimates are crude and may require future improvement, but it is unknown at this time how important these characteristics are to changes in fire behavior. A more intense look at the crown fire model and these input values lies outside the scope of this project.

Attached Vector Files

Additional spatial information was imported into FARSITE to account for roads, trails, and rivers. A separate file was also developed from an intensive soils survey to account for talus or rock occurrences that may not have been captured in the original map. These files were imported as ArcView shape files or barrier files (.BAR). The talus was only used for the Coyote and Robinson fires, as this was not determined to be a major factor influencing fire behavior in the Pelican Valley area fires.

Barrier files may also be created to account for an inactive fire edge, such as occurred after successful suppression efforts on flanks of the Robinson and Tern fires. These .BAR files are incorporated into the simulation to focus on the active edge of the fires.

Attack Menu

Some of these fires involved various forms of management action, including helicopter bucket drops, aerial retardant drops, hand line construction, and black lining, that may have influenced fire spread. FARSITE has the capabilities to incorporate these various forms of suppression activities into the model. These features may be used to simulate actual events as close as possible, providing the suppression efforts were successful. FARSITE assumes that suppression actions, such as line construction, create barriers that are impenetrable to fire spread (Finney 1998).

4.2 WEATHER INPUT (.WTR AND .WND)

Weather data from the local weather stations has been collected from the Mammoth Fire Management archives along with fire management summaries and progression maps of the Coyote, Pelican, and Lost Creek fires of 1996, and the Robinson, Tern, and Raven fires of 1994. Weather data from the NWS and RAWS stations within the park have been converted to the format required by FARSITE. Weather observations were recorded on site during much of the fire activity, and are incorporated into the study as much as possible. Since fire monitors only observe during the day, other sources of data must be incorporated to determine nighttime low temperature, humidity recovery, and wind shifts. Spot weather forecasts provide another source of this data, when available.

Priority was given to on site weather observation data when available. Nearby weather station data were then used to fill in the blanks, with additional site-specific information obtained from spot weather forecasts. YNP has a high density of climatological stations, spread relatively evenly across the landscape, offering relative close proximity of weather station data to most fire locations (see Figure 4.1). The Mammoth weather station was used for the Coyote PNF, while the Lake Meteorological Station was used for the Pelican, Tern, and Raven fires. The Bechler weather station was used for the weather file for the Robinson fire, while the Island Park weather station was found to capture more appropriate wind data for that fire. Forecasted winds, from spot weather forecasts, were also used for the Robinson fire in an attempt to better address the wind-driven events.

4.3 INITIAL FUEL MOISTURES (.FMS)

Since fuel moisture data are not usually collected on site prior to or immediately following ignition, initial values must be estimated from other sources such as weather stations. Fuel moistures were extracted from Fire Family Plus 2.0 (USDA For. Serv. 2000), using Mt. Washburn weather station data, for initial values on August 10, 1996 for the Pelican PNF. The same was done for the 1994 fires, with fuel moisture values taken from MT. Washburn on August 5 for both the Tern and Raven fires and Mt. Sheridan on September 9 for the Robinson fire. Unfortunately, the 1994 weather data from Bechler was unavailable in the Fire Family plus database and therefore the fuel moistures could not be obtained. Since Mt. Sheridan has been used previously to represent conditions park-wide (Renkin pers. comm.), fuel moistures from this weather station were used for the Robinson fire.

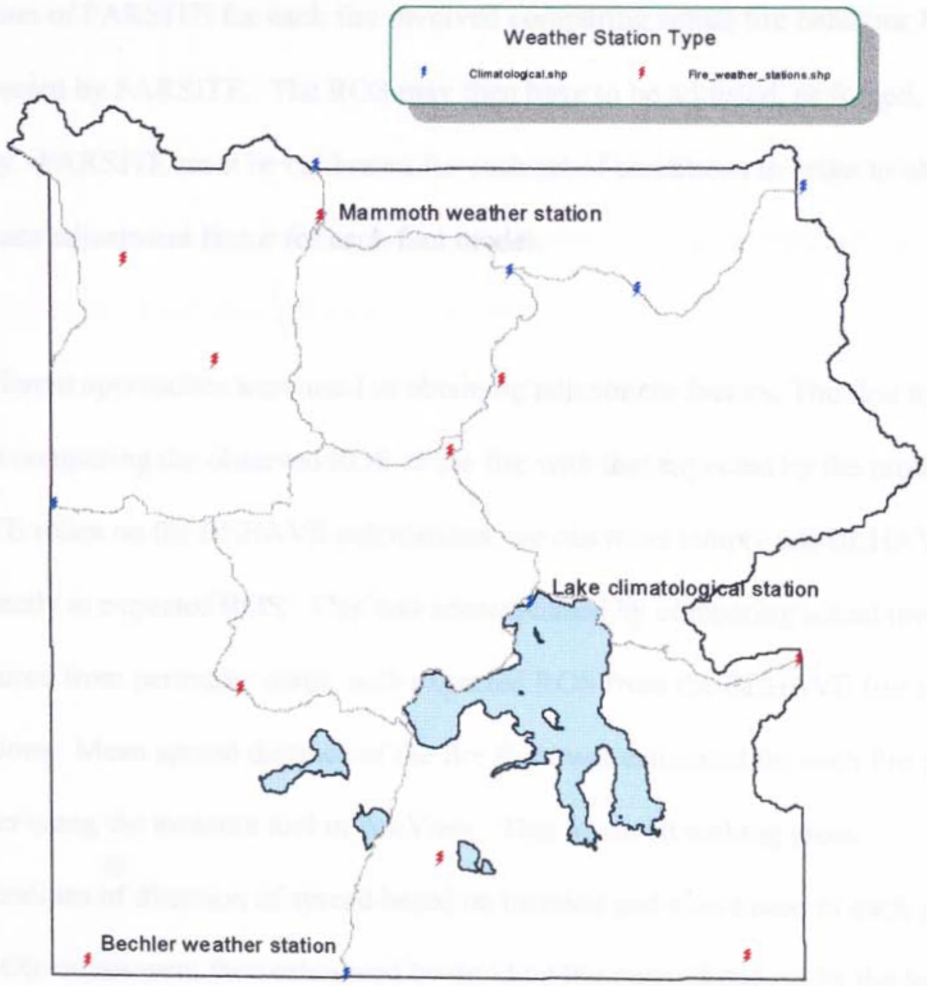


Figure 4.1. Distribution of weather stations across the Yellowstone National Park landscape.

Fuel moistures were recorded on site during the course of the 1996 Coyote and Pelican PNFs. Because the Coyote fire remained inactive during the first six weeks, on site measurements of fuel moistures recorded on July 26 were used as the initial values, with the wind and weather stream data also beginning on this date.

4.4 CALIBRATION (.ADJ)

Calibration of FARSITE for each fire involved comparing actual fire behavior ROS to that expected by FARSITE. The ROS may then have to be adjusted, or forced, to better fit reality. FARSITE must be calibrated for each set of conditions in order to obtain an appropriate adjustment factor for each fuel model.

Two different approaches were used in obtaining adjustment factors. The first approach involves comparing the observed ROS of the fire with that expected by the model. Since FARSITE relies on the BEHAVE calculations, we can more simply use BEHAVE to look directly at expected ROS. This was accomplished by comparing actual mean ROS, as measured from perimeter maps, with expected ROS from the BEHAVE fire behavior calculations. Mean spread distance of the fire front was estimated for each fire growth perimeter using the measure tool in ArcView. This involved making gross generalizations of direction of spread based on location and orientation of each perimeter. Mean ROS values were then calculated by dividing the mean distances by the length of time, in hours, over which the fire burned.

The estimated fuel moistures from FARSITE input were then input into BEHAVE, along with a range of wind and slope parameters, to calculate ROS for each fuel model. The BEHAVE ROS were then compared with the average ROS from the perimeter maps to calibrate FARSITE under the given fuel and weather inputs, using average daily wind speeds and slopes for each fire.

Adjustment factors were calculated by dividing the actual ROS by the expected ROS from BEHAVE. This was done for both the actual time lapsed, as well as for more appropriate time periods for active fire growth. For a single 24-hour time period between perimeters, 8 or 12-hour average ROS may be used to simulate the active burn period, thus avoiding nighttime conditions under which fire growth rarely occurs. During the Robinson fire, multiple perimeters were recorded on extreme days and 4-hour average ROS are available to simulate shorter burn periods. For other fires, perimeters may span a several day period in which fire growth may have occurred only during a single period. In this case, efforts were made to simulate only the active fire spread as noted by fire monitors.

The second approach involved running a simulation multiple times, altering only this adjustment factor to reach a good fit. Starting with an adjustment factor of 1.0, one can determine if fire spread is over or under predicted by the model. More than likely, for long-range scenarios, this model will over predict fire spread. In this case, the next step would be to split the difference between 1.0 and 0 by inputting an adjustment factor of 0.5. From that point, one should then split the difference again to systematically narrow down a suitable adjustment factor (S493 Class Notes). Keeping in mind that this must be done for each fuel model present, and that the conditions under which the model is calibrated continually change during the course of a single fire, this can be a crude and time consuming process.

Parameter Settings

Parameter settings for short simulations (24 hours or less) were set at shorter time steps of 2 or 3 hours, with visible time steps set to match the simulation period. For time periods of greater than 24 hours, time step was set to the maximum of 6 hours between calculations and 24 hours for visible time step. Perimeter and distance resolution depended on time step and initial perimeter size. Usually, both of these settings were kept at 150 meters to avoid the eventual bogging down of the calculation process as the perimeters increased.

These parameter settings were made adjustable in order to accommodate computer and time limitation, yet these settings may override the resolution of the input data. The user has the ability to manipulate these parameters to best fit the situation, yet it is important to remember the possible loss of resolution in identifying the appropriate settings. Imported barrier files are adjusted automatically by FARSITE to remain effective despite parameter settings.

4.5 VALIDATION

Validation should be accomplished by simulating only periods of active fire spread in order to avoid large errors. Because FARSITE does not address smoldering combustion, which commonly occurs for one or more burn periods following a precipitation event, analysis of non-active burn periods should be minimized.

Fire behavior observations for the 1996 Coyote and Pelican PNFs were well documented and daily progression maps corresponded well to that activity. The 1994 fires, however, were managed as wildfires, and fire activity was not consistently documented for monitoring purposes. The transition of fires from local management to Type 2 overhead teams in 1994 also created inconsistencies in fire activity documentation, as well as record filing. Fire Behavior Analysts were concerned with forecasting potential fire behavior for the upcoming shift for planning and safety efforts rather than documenting actual fire behavior that was observed. For this reason, fire activity can only be assumed to correspond with recorded perimeter growth, by date and time of the mapping effort.

Daily fire monitor reports for the 1996 Coyote and Pelican fires have been consolidated into tabular format (Tables 5.1 and 5.2) in order to identify specific fire behavior "events" that may be simulated using FARSITE. Fire activity tables were also created for the 1994 Robinson fire (Table 5.4) using fire management narratives. Very little fire activity documentation could be found for the 1994 Tern and Raven fires, and tables 5.5 and 5.6 were created referring to fire perimeter maps alone.

Simulations were then run for active burn periods of each fire. Adjustment factors were initially set to that determined by the actual ROS/expected ROS approach. Occasionally, these adjustment factors were still not appropriate and further adjustments were made using the second approach.

Simulations were initiated from imported ignition files created from the actual perimeters that had been recorded and digitized into GIS. These files required some manipulation in ArcView to create shapefiles compatible with FARSITE. Small spots outside the main fire were omitted unless significant growth had been experienced. Simulations were run for each time period from one perimeter to the next for each fire.

Simulations were selected from each fire to account for short (up to 1 day), mid (2-5 days), and long-range (> 5 days) projections. The mid- and long-range projections included periods of low fire activity, while short-range projections were limited to active burn periods as described above. Although there were many possible simulations, only four were chosen from each fire for further analysis. These were selected primarily on the above criteria in addition to the observed performance of FARSITE and duration of computer simulations. The longer simulations involving larger perimeters often took several hours to complete and re-adjustment and re-simulation (often required more than once) was not always feasible due to time constraints. FARSITE perimeters were then exported as shapefiles and overlaid with the actual perimeters in ArcView. The fuel model spatial layer was also included for this evaluation.

Overlay analysis of observed over predicted fire perimeters allows for four possible outcomes for each cell: 1) observed and predicted to burn, 2) observed but not predicted to burn, 3) predicted but not observed to burn, or 4) neither observed nor predicted to burn. The 4th outcome is boundless, and therefore excluded from the analysis.

4.6 PROJECTION OF THE LOST CREEK FIRE

The Lost Creek fire of 1996 was simulated using no adjustment (.ADJ =1.0 for all fuel models) to project potential fire growth without management action. Simulations were run for the periods of August 31, when suppression actions had initially controlled this fire, through September 4 (an active period for the Coyote fire) as well as through September 11, the end of the active fire season as exhibited by both the Coyote and Pelican PNFs. Using the calibrations from the Coyote Fire, the Lost Creek fire of was again run through FARSITE to predict potential fire spread for both time periods.

Weather data from the Tower climatological station included daily high and low temperature, 24-hour precipitation amount, and winds and sky conditions as observed once daily, usually in the morning. Data from the Coyote fire was used for relative humidity while winds were used from the Mammoth weather station. The wind data recorded on the Coyote fire had been noted by fire monitors to be locally influenced by terrain, notably the Hellroaring Canyon. The Coyote .WND and .WTR files had originally included data from the Mammoth weather station to supplement on site observations.

5.0 FIRE OBSERVATIONS

5.1 1994 FIRE SEASON

A range of fire behavior, from intense to extreme interspersed by periods of smoldering and creeping surface fire, characterized the 1994 fire season. A total of 64 wildfires burned about 16,000 acres, including the 8,514-acre Robinson fire (Table 3.1). Additional fires included four PNFs and two wildfires that were managed in the confine strategy. These two fires, the Tern and Raven, burned almost 8,500 acres.

Thousand hour fuel moistures at the Sheridan weather station approached the 13% threshold for large fire activity by mid August and remained low throughout much of September (Figure 5.7). The Mammoth weather station reached this threshold earlier, with 1000-hr fuel moistures approaching 13% by late July (Figure 5.8). This corresponds with the active burning season, with several fires, including the Tern and Raven, becoming active in early August.

ERC trends during the 1994 fire season were well above the 35-year average, and exceeded the 90th percentile for much of the period from mid-August through mid-September (see Figure 5.9). Unfortunately, the Sheridan weather station was shut down prior to the end of the active fire season, so the Mammoth station is also included (Figure 5.10). ERCs dipped down below average in mid-September and peaked again at the 90th percentile later in the month. This corresponds with the fire behavior pattern exhibited by the Robinson fire.

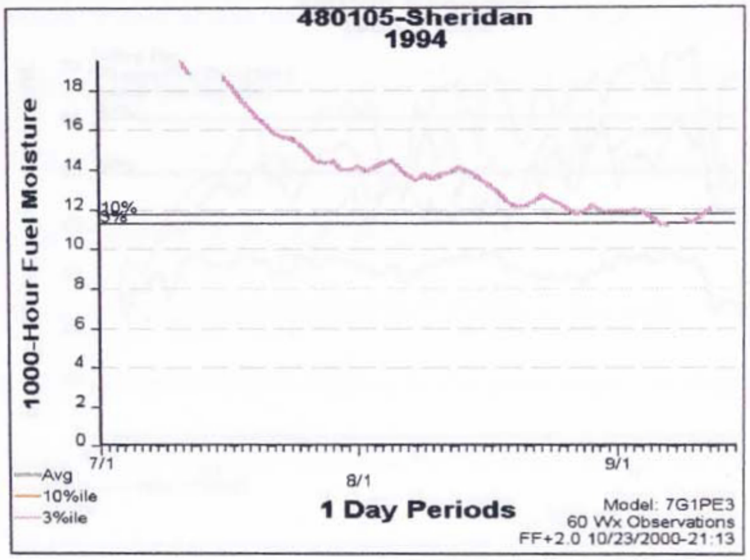


Figure 5.1 Thousand-hour fuel moistures as calculated from the Mt. Sheridan weather station during the 1994 fire season (adapted from Fire Family Plus; USDA For. Serv. 2000).

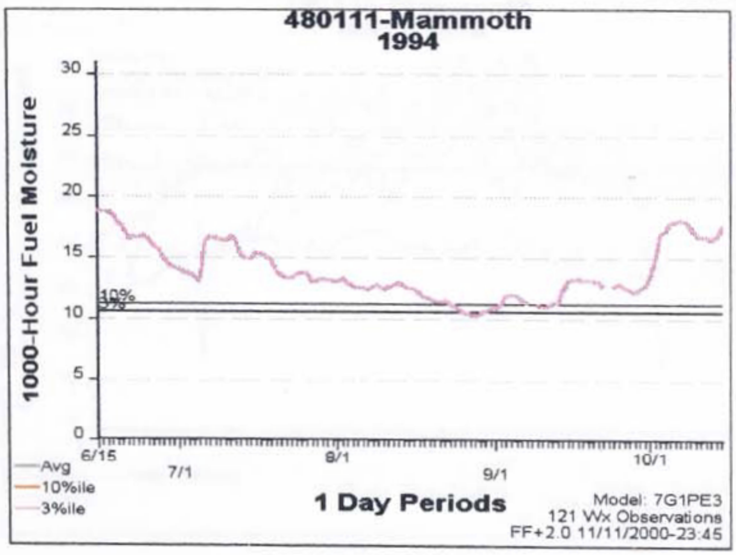


Figure 5.2 Thousand hour fuel moistures measured at the Mammoth weather station during the 1994 fire season (Adapted from Fire Family Plus; USDA For. Serv. 2000).

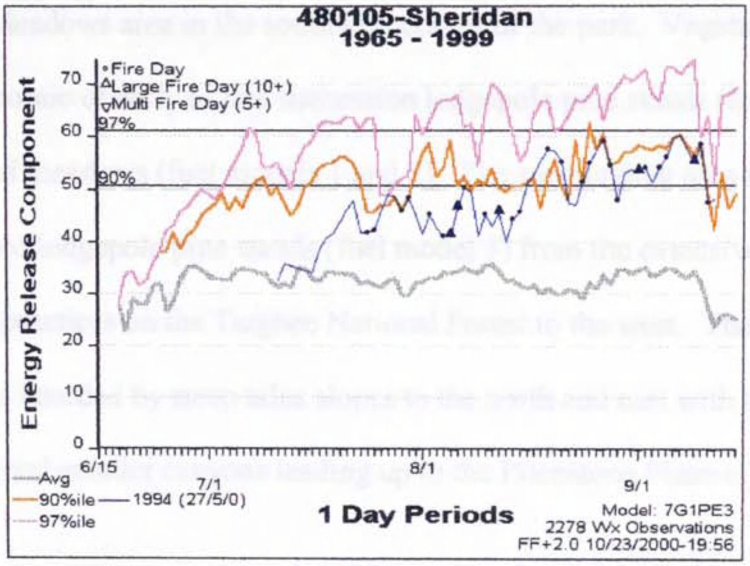


Figure 5.3 ERC as calculated from the Mt. Sheridan weather station during the 1994 fire season (Adapted from Fire Family Plus; USDA For. Serv. 2000).

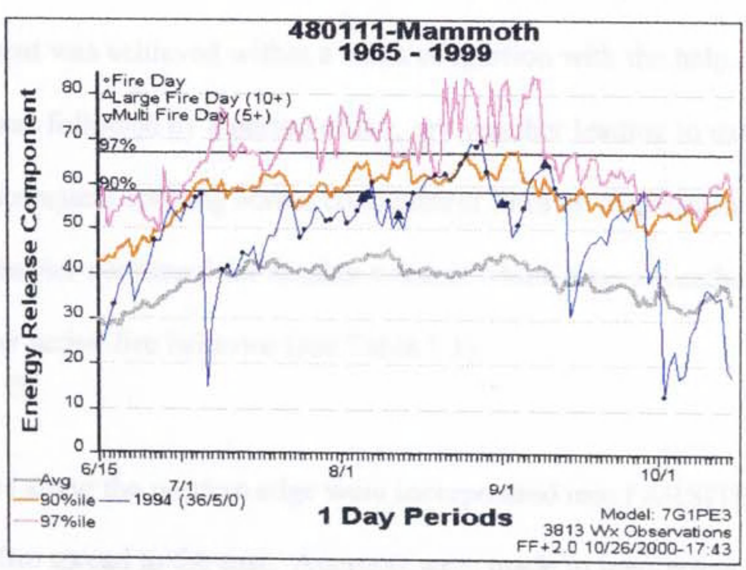


Figure 5.4 ERC as calculated form the Mammoth weather station during the 1994 fire season (adapted from Fire Family Plus; USDA For. Serv. 2000).

5.1.1 1994 ROBINSON FIRE

The Robinson fire ignited at 1300 on September 9 and subsequently burned 8,514 acres in the Bechler Meadows area in the southwest corner of the park. Vegetation cover consisted of a mosaic of early to late succession lodgepole pine stands (fuel models 8 and 10) and scattered meadows (fuel models 1 and 2). The surrounding area included recently disturbed lodgepole pine stands (fuel model 5) from the extensive 1988 fires as well as logging practices on the Targhee National Forest to the west. The Bechler meadows area is boarded by steep talus slopes to the north and east with the Bechler Canyon and several smaller canyons leading up to the Pitchstone Plateau.

This fire was declared a wildfire due to its proximity to the boundary. Suppression actions included line construction along the northern, western and southern perimeter to prevent fire spread across jurisdictional boundaries onto the Targhee National Forest. Initial containment was achieved within a week of ignition with the help of cool, wet weather. This was followed by a period of hot, dry weather leading to extreme fire behavior and subsequent spotting across containment lines on the eastern edge of the fire. Extreme fire behavior continued for another week at which time a weather event prevented further active fire behavior (see Table 5.1).

The control lines along the western edge were incorporated into FARSITE runs to concentrate on fire spread to the east. Attempts were made to incorporate FARSITE's attack method menu to recreate successful suppression actions. Due to limitations on computer speed and memory, the current version of FARSITE does not allow for easy manipulation of these parameters during the simulation, and the line construction could not be stopped when necessary. Consequently, FARSITE contained the fire at a relatively small size and the simulation could not proceed. A second approach to this problem is to create a barrier file that may be imported to stop the spread of fire along the suppressed or cold edge.

Weather data from the Bechler weather station was used to complete the .WTR file for this fire, while the Island Park station was used to complete the .WND files. This weather station, however, did not capture the west, southwesterly winds that obviously drove much of the fire activity. Spot weather forecasts were obtained on a daily basis for this fire and several burn periods were forecasted to have very strong southwesterly winds. These forecasted winds were used to complete the .WND file for this fire.

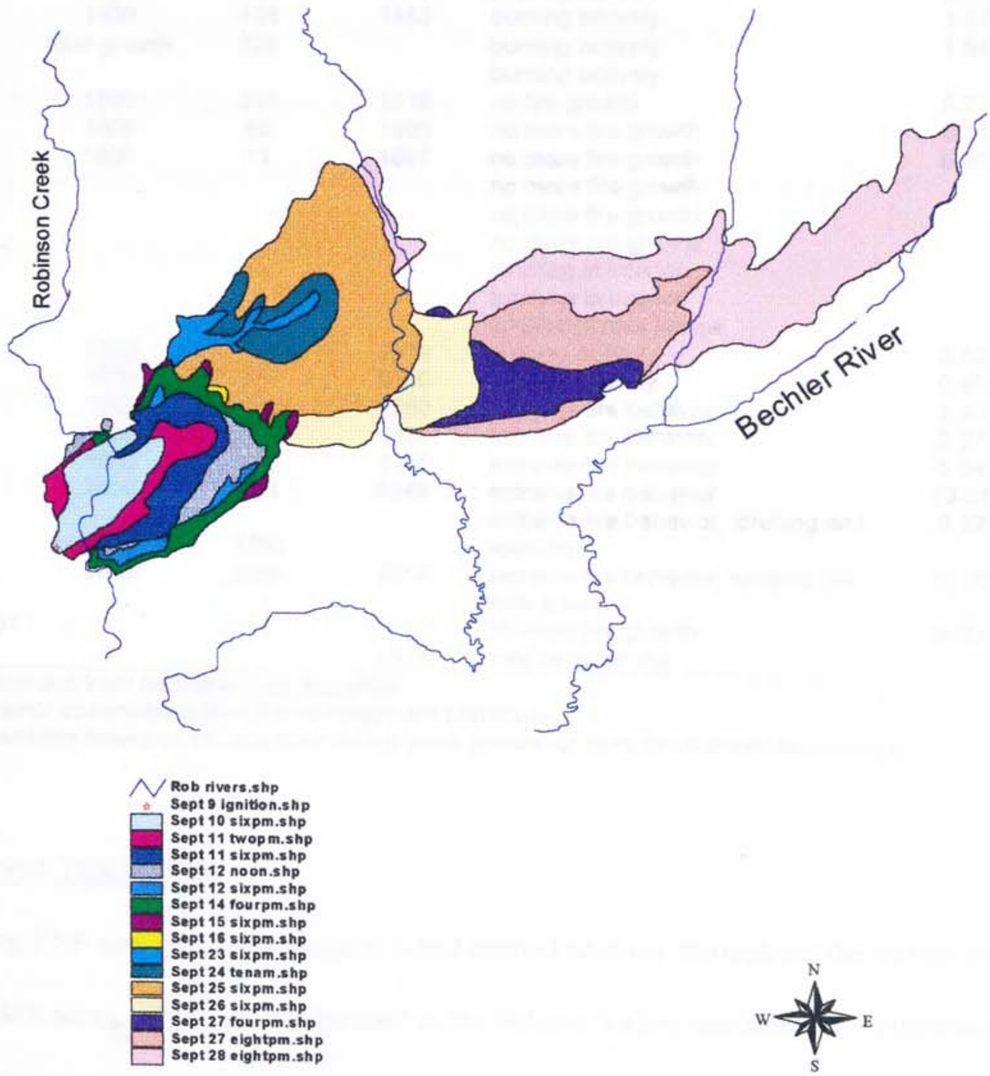


Figure 5.5. Progression of the 1994 Robinson fire.

Table 5.1. 1994 Robinson Fire activity.

Date	Time	fire growth (acres)[a]	total fire size (acres)[a]	fire behavior observations[b]	Estimated ROS (Ch/hr)[c]
9/9	1302			burning actively	
9/10	1400	436	436	burning actively	4.77
9/11	1400	290	726	burning actively	2.14
	1800	401	1127	burning actively	6.96
	total growth	691		burning actively	2.94
9/12	1200	221	1348	burning actively	1.93
	1800	105	1453	burning actively	1.57
	total growth	326		burning actively	1.84
9/13				burning actively	
9/14	1800	365	1818	no fire growth	0.27
9/15	1800	68	1886	no more fire growth	0.31
9/16	1800	11	1897	no more fire growth	0.29
9/17				no more fire growth	
9/18				no more fire growth	
9/19				no more fire growth	
9/20				torching in interior	
9/21				torching in interior	
9/22				spotted across fireline	
9/23	1800	182	2079	burning actively	3.40
9/24	1000	371	2450	burning actively	0.93
9/25	1800	1812	4262	extreme fire behavior	2.80
9/26	1800	597	4859	extreme fire behavior	2.07
9/27	1600	488	5347	extreme fire behavior	5.54
	2000	902	6249	extreme fire behavior	23.61
	total growth	1390		extreme fire behavior, torching and spotting	8.32
9/28	2000	2265	8514	extreme fire behavior, spotting 3/4 mile ahead	10.36
10/1-10/31				no more fire growth	0.00
10/31			8514	Fire declared out	

[a] acres recorded from perimeter mapping effort
[b] fire behavior observations from fire management narratives
[c] ROS estimates based on 24-hour time period times number of days since previous perimeter

5.1.2 1994 TERN FIRE

The Tern PNF was ignited on August 6 and burned actively throughout the month for a total 4,888 acres. This fire was located in the Pelican Valley northeast of Yellowstone Lake. The Raven PNF started on August 12 and burned 3,570 acres to the east of the Tern Fire. Although these fires were not declared PNFs, they were managed under the confine strategy. Suppression activities on the Tern fire focussed on the western edge, preventing the spread toward the Fishing Bridge developed area, while activities on the Raven fire were limited to structure protection of backcountry cabins and monitoring.

Vegetation in this area consisted primarily of lodgepole pine with a spruce/fir component represented by fuel models 8 and 10. Much of this area has previously been disturbed by fire, replacing these stands with new growth in the seedling and sapling stages. These areas, represented by fuel model 5, were rarely involved inside the perimeters of either of these fires. More recently burned areas may have impeded fire spread due to lack of available fuels. Although much of the open valley of this area is represented by fuel model 2, sagebrush grasslands, the fire spread little in this fuel type until late August. Perhaps this is due to late season curing of the grasses. A few small wet meadows, represented by fuel model 1, were present within the perimeters, but fire activity may have remained low here as well.

Weather observations were recorded on the Tern fire. Weather data from the Lake meteorological station (NPS Air Resources Division) was used to complete the .WTR and .WND files. The reliability of this data for the lower Pelican Valley has been previously determined with the 1996 Pelican PNF, located in close proximity to the southwestern edge of the Tern fire (see Figure 1.1). Due to the proximity of these two fires, weather recorded on the Tern is assumed to be adequate for the Raven PNF as well. The same wind and weather streams were used for both the Tern and Raven fires.

Tables 5.3 and 5.4 were created for each of these fires to summarize fire activity. Fire behavior exhibited by both of these fires can only be determined by perimeter maps (Figure 5.6), as no recorded observations were found. Perimeters were not always mapped at the same time for these fires, making it more difficult to appropriately compare fire growth between the two fires. However, it must be assumed that, due to the close proximity, these fires experienced similar burning conditions at the same time.

It may be assumed that some periods of torching and short-range spotting may have occurred in area represented by fuel model 10, as well as possible short duration crown fires. These fires did exhibit occasional periods of "extreme" fire behavior (Renkin pers. comm.).

Table 5.2. 1994 Tern PNF Fire Activity

Date	fire growth (acres)	total fire size (acres)	Estimated ROS (Ch/hr)[a]
8/6	ignition		
8/20	1513	1513	0.31
8/21	373	1886	2.90
8/23	65	1951	[b]
8/24	1684	3635	2.28
8/26	1083	4718	1.24
8/27	150	4868	1.04
8/30	20	4888	[b]

[a]ROS estimates based on 24-hour time period times number of days since last perimeter
[b]minimal spot fire growth only

Table 5.3. 1994 Raven PNF Fire Activity

Date	Fire growth (acres)	total fire size (acres)	Estimated ROS (Ch/hr)[a]
8/12	Ignition		
8/20	324	324	0.39
8/21	139	463	1.16
8/23	274	737	0.62
8/26	205	942	0.41
8/27	1006	1948	6.17
8/30	1622	3570	1.17

[a]ROS estimates based on 24-hour time periods times number of days since previous perimeter

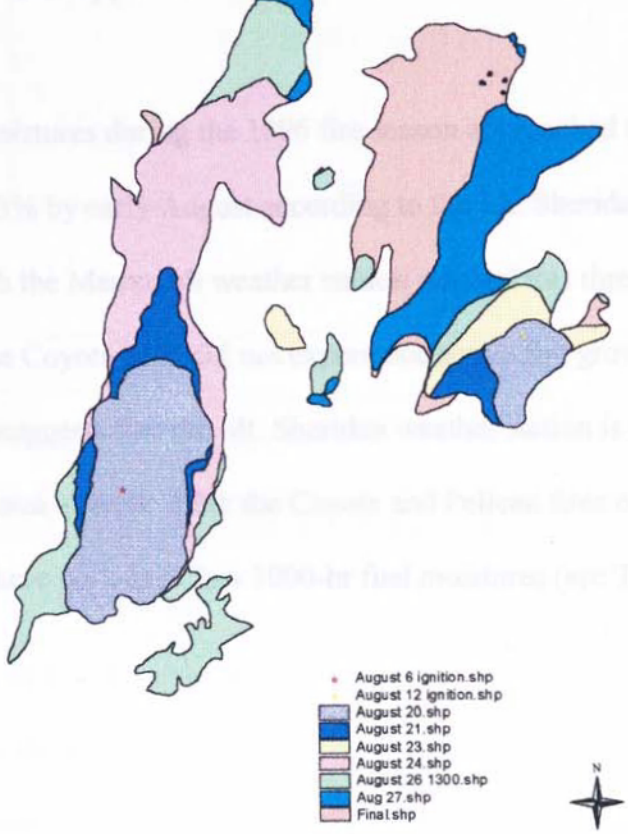


Figure 5.6 Progression of the 1994 Tern and Raven fires.

5.2 1996 FIRE SEASON

The 1996 fire season in YNP was characterized by "normal" smoldering fire activity interspersed with occasional periods of "intense" burning conditions, as described in the YNP Wildland Fire Management Plan (1992). Of a total of 19 lightning-caused fires in the park, 12 were managed successfully as Prescribed Natural Fires (PNF) burning 3,264 acres within park boundaries (see Table 3.1). Only two of these fires, the Coyote and the Pelican, experienced "intense" burning conditions that allowed them to reach significant acreage. An additional fire, the Lost Creek Fire, was initially treated as a PNF, but was converted to a wildfire and suppressed after it had burned 3.5 acres.

Thousand hour fuel moistures during the 1996 fire season approached the large fire activity threshold of 13% by early August according to the Mt. Sheridan weather data (Figure 5.7). Although the Mammoth weather station reached this threshold a month earlier (Figure 5.8), the Coyote PNF did not experience active fire growth until early August. Perhaps this suggests that the Mt. Sheridan weather station is still more representative of this area as well. Both the Coyote and Pelican fires exhibited intense fire behavior during these periods of low 1000-hr fuel moistures (see Tables 5.4 and 5.5).

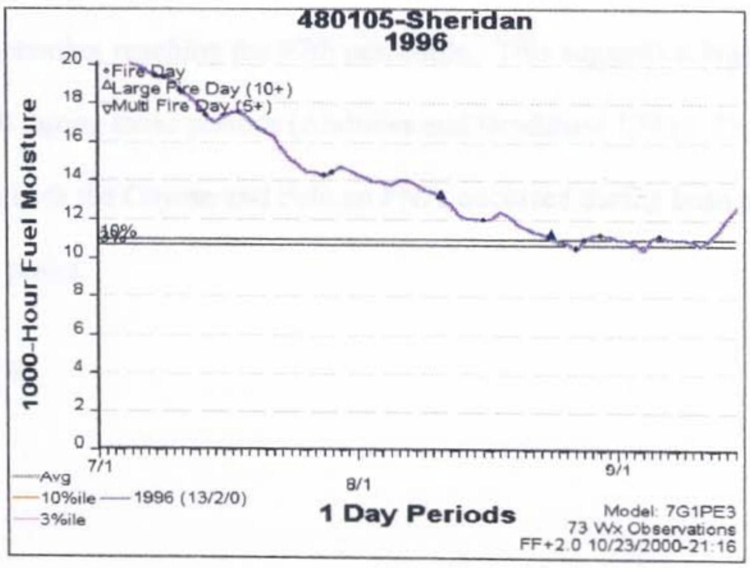


Figure 5.7. Thousand-hour fuel moisture measured at the Mt. Sheridan weather station during the 1996 fire season (adapted from Fire Family Plus; USDA For. Serv. 2000).

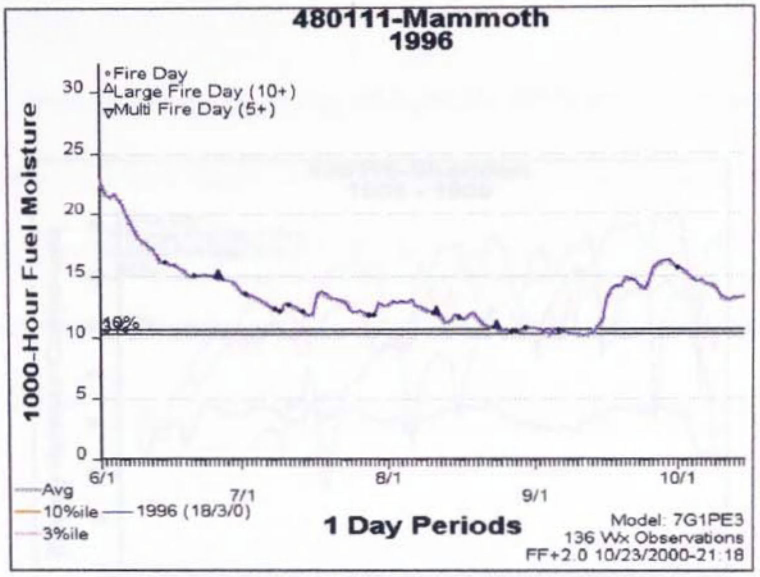


Figure 5.8 Thousand-hour fuel moisture measured at the Mammoth weather station during the 1996 fire season (adapted from Fire Family Plus; USDA For. Serv. 2000).

ERC trends for 1996 were well above the 35-year average (1965-1999), occasionally reaching or exceeding the 90th percentile for both Mt. Sheridan and Mammoth weather stations (Figures 5.9 and 5.10), with a couple of short peaks in late August and the beginning of September reaching the 97th percentile. This suggests a high potential for large fire growth during these periods (Andrews and Bradshaw 1996). Periods of intense fire behavior on both the Coyote and Pelican PNFs occurred during burn periods following these peaks.

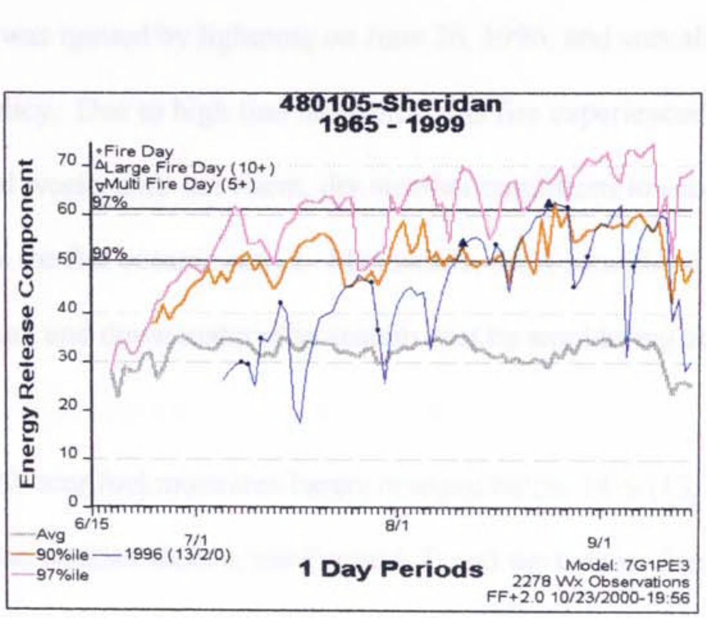


Figure 5.9 ERC values estimated from the Mt. Sheridan weather station during the 1996 fire season (Adapted from Fire Family Plus; USDA For. Serv. 2000)

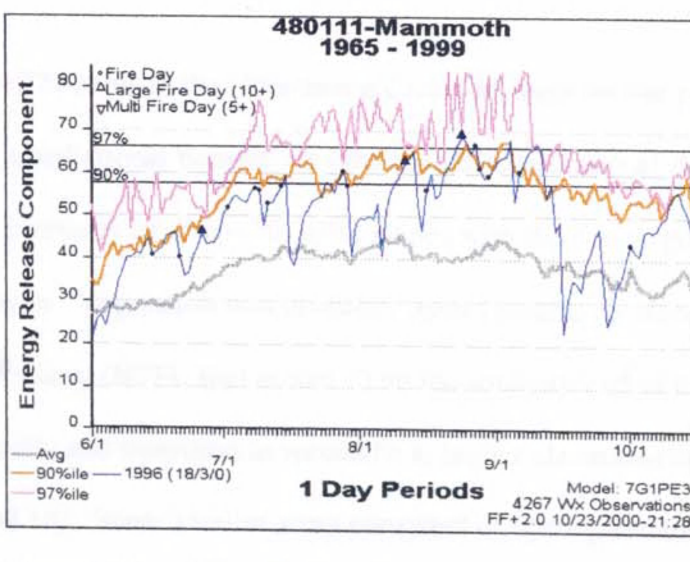


Figure 5.10 Energy Release Component from Mammoth weather station, 1996 (adapted from Fire Family Plus; USDA For. Serv. 2000).

5.2.1 COYOTE PNF

The Coyote PNF was ignited by lightning on June 26, 1996, and was allowed to burn under the PNF policy. Due to high fuel moistures, this fire experienced very little fire activity for several weeks until the warm, dry weather conditions lowered fuel moistures to the point where the fire became active. Meanwhile, fuels conditions did allow for the duff and heavy dead and down material to sustain heat by smoldering combustion.

By August 5, 1000-hour fuel moistures barely dropped below 14% (13.7% as measured by the Mt. Sheridan weather station, see Figure 5.7) and the Coyote fire became active. Although the Mammoth weather station, which is located relatively close to the Coyote fire, recorded 1000-hr fuel moistures below 14% by early July (Figure 5.8). However, the trends in 1000-hr fuel moisture and fire behavior for YNP have been established using Mt. Sheridan weather data (Renkin and Despain 1992).

This fire burned 4,271 acres in the Hellroaring Creek drainage on the park's northern range and across jurisdictional boundaries onto the Gallatin National Forest. Terrain in this area consists primarily of steep (20-30%) slopes with the fire originating in the bottom of the canyon. Vegetation was primarily open Douglas-fir stands with pinegrass or snowberry understory (NFFL fuel model 2) on the southern end of the fire, with increased tree density and transition to spruce/fir at higher elevations outside the park (fuel models 8 and 10). Some smaller areas consisted of open grasslands (fuel model 1) or recently burned or disturbed stands (fuel model 5).

Hellroaring Mountain, located directly to the west of the ignition, has sparse vegetation cover. This unique feature, which stands prominently in the landscape as a rock-covered peak, prevented fire spread up the steep slopes to the west. Unfortunately, this critical fuel break was not captured by the Grizzly Bear Habitat Mapping effort.

Between this first active burn period of August 5 and September 29, when the fire was officially declared "out," the status of the fire activity varied greatly due to changing conditions. Several times during this period, precipitation events led to one or more "inactive" burn periods during which the fire was merely sustained by smoldering in the duff and large diameter dead and down fuels (See Table 5.7). This type of fire activity, common in the Yellowstone area (Sellers and Despain 1976), is not addressed by current fire behavior models, and therefore, can not be simulated in FARSITE.

Fire monitors had witnessed light variable winds, or eddies, at certain locations on the fire due to the steep canyon terrain. These winds often pushed the creeping ground fire back into the fire perimeter and prevented further spread up canyon until conditions changed.

During more active burning conditions, fire spread more readily through the surface fuels, torching trees and/or spreading passively through the crowns. Short-range spotting was frequently observed, and spot fire growth contributed greatly to overall fire spread. More often, however, the fire remained inactive due to precipitation events and high relative humidities. Figure 5.11 shows the progression of the Coyote PNF throughout the season while Table 5.7 described the periods of fire activity as recorded by fire monitors.

This PNF was an interagency collaborative effort that, with the presence of a Prescribed Fire Incident Management Team, allowed for intensive monitoring and data collection. There was a considerable amount of data collected for the Coyote PNF, as fire monitors remained on scene throughout the course of the fire. For periods lacking these observations, most typically nighttime, weather data was incorporated from the Mammoth weather station and spot weather forecasts.

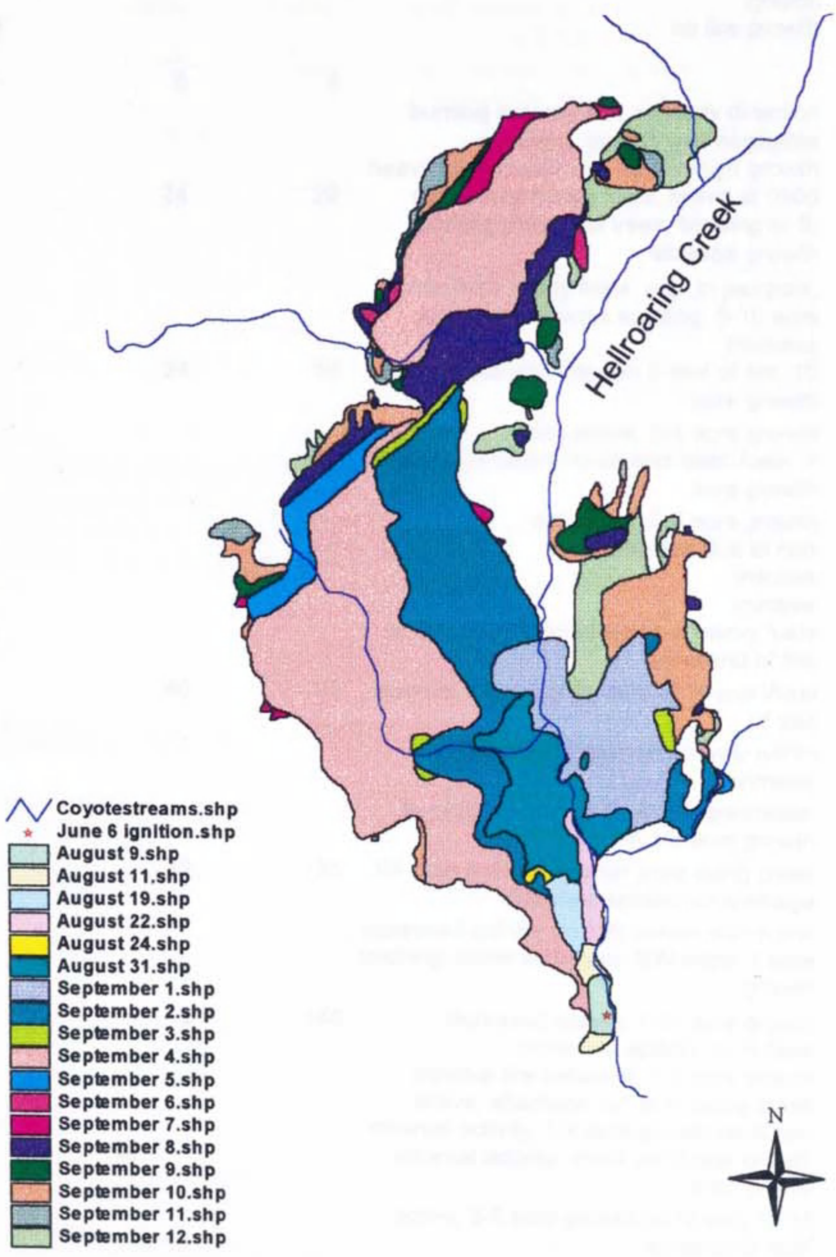


Figure 5.11 Progression of the Coyote PNF throughout the 1996 fire season.

Table 5.4 1996 Coyote PNF Fire Activity

Date	Fire growth (acres)a	Total fire size (acres)[a]	Observed fire activity[b]	Estimated ROS (Ch/hr)[c]
6/26			ignition	
6/27 TO 8/4			no fire growth	
8/5	5	5		
8/6			burning actively in a westerly direction	
8/7			creeping, growth was negligible	
8/8			heavy logs consumed, no acreage growth	
8/9	24	29	consumed heavy fuels, active at 1600 torching individual trees, backing to S, acreage growth	0.26
8/10			consumed heavy fuels, esp. in jackpots, some short-range spotting, 5-10 acre increase	
8/11	24	53	burned actively, esp. on S end of fire, 10 acre growth	0.3
8/12			less active, 3-4 acre growth	
8/13			creeping in heavy down and dead fuels, 3 acre growth	
8/14			not active, 3-5 acre growth	
8/15			inactive due to rain	
8/16			inactive	
8/17			inactive	
8/18			no fire growth, smoldering in heavy fuels on N end of fire	
8/19	40	93	inactive, most activity was on N end West of trail	0.17
8/20			no fire growth, burned actively within perimeter	
8/21			burned in heavy fuels inside perimeter, 1/4-1/2 acre growth	
8/22	42	135	1/4 acre growth, riparian area along creek impeding spread up drainage	0.47
8/23			increased activity on NW corner with some torching, some activity on SW edge, 1 acre growth	
8/24	5	140	increased activity 7-10 acre growth	0.17
8/25			moderate activity on N flank	
8/26			minimal fire behavior, 1-2 acre growth	
8/27			active, afternoon run to N along creek	
8/28			minimal activity, 1/4 acre growth on N end	
8/29			minimal activity, spots on N side of trail, min. growth	
8/30			active, 3-5 acre growth on N end, 12-15 acres on S end[d]	
8/31	252	392	low to moderate activity, localized crowning runs about 10 acres, the rest was surface spread to N up drainage	0.3
9/1	379	771	active surface fire spread up drainage on E side of creek, isolated crowning. Ran and spotted up Bull Mt. decreased in activity at ridgeline	1.76

9/2	657	1428	slope-driven run up SE facing slope W of creek due N to ridge and died down, short-range spotting, 500 acre growth	4.33
9/3	41	1469	minimal activity limited to downslope spread and heavy fuel burnout, 28 acre growth	0.1
9/4	1523	2992	rapid growth, spotting, burned actively through night in thermal belt	2.82
9/5	113	3105	minimal fire growth and activity, MIST actions taken on SW flank along ridge	0.43
9/6	22	3127	no growth	0.21
9/7	53	3180	inactive, holding actions along ridge	0.32
9/8	247	3427	minimal growth +5 acres	0.93
9/9	109	3536	active surface fire some torching	0.36
9/10	374	3910	ground fire with occasional torching	1.06
9/11	60	3970	active fire behavior, went out in meadow, spotting across Horse Ck.	0.46
9/12	301	4271	reduced activity	1.09
9/13			minimal fire activity, no growth	
9/14 TO 10/28			inactive, no growth	
10/28		4271	fire declared OUT	

[a] Acres recorded from perimeter map.
[b] Fire behavior from fire monitor narratives.
[c] ROS estimates based on 24-hour time periods times the number of days since previous perimeter.
[d] 30-50% of area unburned rock (8/30 Daily Report).

5.2.2 1996 PELICAN PNF

The Pelican PNF was ignited by lightning on the afternoon of August 11 and subsequently burned 1,524 acres in the Pelican Valley area to the northeast of Yellowstone Lake. This area historically has a higher fire occurrence than many areas in the park due to the prevailing southwesterly winds bringing storms off of the lake.

Terrain in this area consists primarily of open valley with slopes of 20% or less. Vegetation in the area of the main fire consisted primarily of dense lodgepole stands with a spruce/fir component and heavy fuel loading (fuel models 8 and 10). The large spot fires occurred in recently burned lodgepole pine stands (fuel model 5) with small areas of open grasslands (fuel model 1 and 2) and younger lodgepole pine stands (fuel model 8).

Fire monitors were on site during most active burn periods of this fire recording weather and fire behavior. During inactive burn periods, however, the smoke column was monitored from the Lake developed area and no weather observations were recorded. Due to this inconsistency in data collection, and the fact that nighttime low temperature and high relative humidity are not captured by the monitors, other sources of weather data had to be incorporated for a complete .WTR file.

The nearest fire weather stations are at Canyon or Mt. Washburn. Neither of these stations captures an accurate wind pattern for the Pelican Valley, which receives most of its daytime wind and weather off of the Lake to the south, southwest. The lake may also influence Temperatures and relative humidities. The National Park Service Air Resources Division has a station located in the Lake developed area for collecting ambient air quality and meteorological data. This meteorological station records hourly data including temperature, relative humidity, dew point, peak and scalar wind speeds and direction, and solar radiation.

Data from the Lake meteorological station was used to create a complete wind stream, as well as to fill in data missing from the observations for the .WTR file. These hourly observations provide better wind resolution than the typical weather stations that only record 10-minute average values once daily. This data was compared to wind observations on the fire and considered appropriate enough to provide a more detailed wind stream for the Pelican fire.

Like the Coyote fire, the Pelican PNF experienced a wide variety of fire behavior throughout the course of the season (Table 5.9). Occasional periods of active fire spread were interspersed with periods of creeping and smoldering in the heavy fuels and duff. Active periods were characterized by isolated torching with short-range spotting and occasional passive crown fire and mid- to long-range spotting in areas of fuel model 10. The meadows classified as fuel model 1 did not exhibit much fire growth, likely due to the high fuel moistures retained in the not yet cured grasses.

Fire monitors witnessed several active burn periods in which little or no perimeter growth occurred. Surface fire spread and torching in the interior of the fire was frequent as unburned islands common in the mosaic pattern of Yellowstone area fires were gradually consumed.

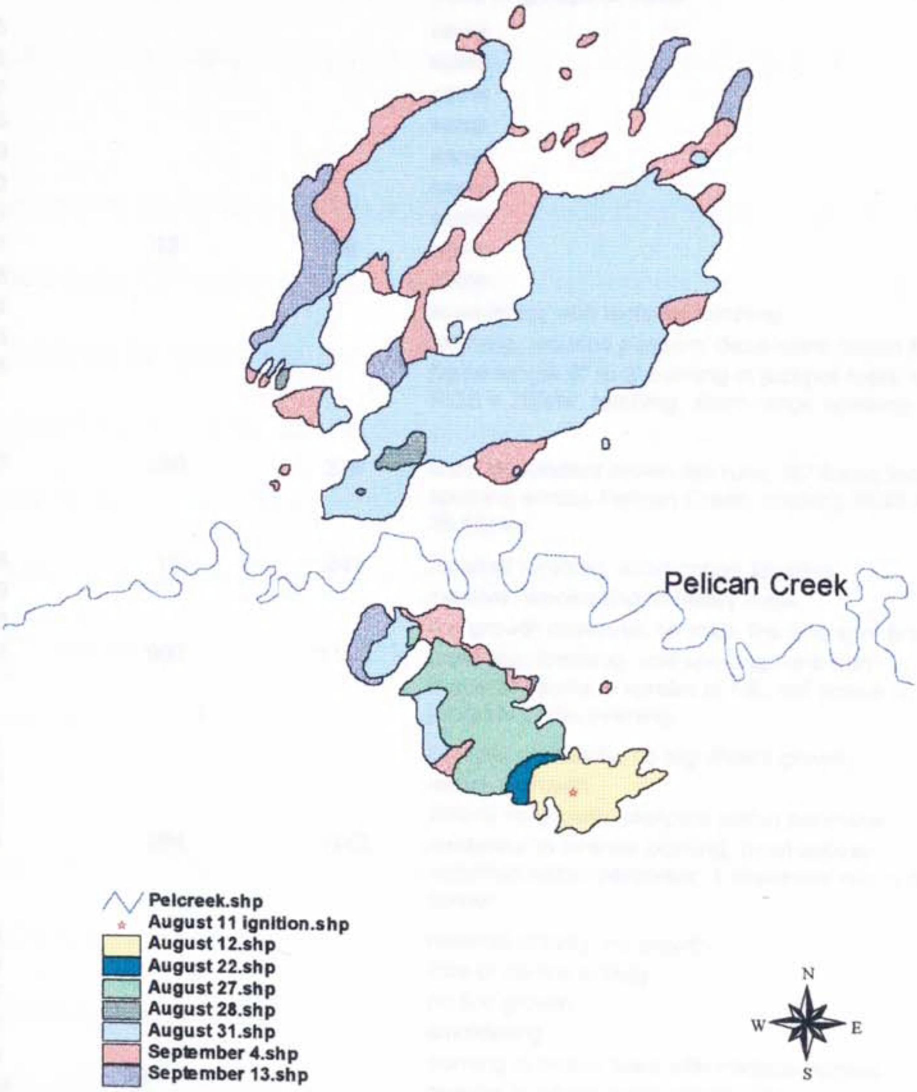


Figure 5.12 Progression of the 1996 Pelican PNF.

Table 5.5 1996 Pelican PNF Fire Activity

Date	Fire growth recorded (acres)[a]	total fire size (acres)[a]	fire behavior observations[b]	Estimated ROS (Ch/hr)[c]
8/11	0.1	0.1	Ignition	
8/12	74	74	burned actively	2.68
8/13				
8/14			creeping in dead and down fuels, torching single trees or groups of trees	
8/15			same	
8/16			same	
8/17			same	
8/18			same	
8/19			same	
8/20			same	
8/21			same	
8/22	12	86	same	0.03
8/23			same	
8/24			smoldering with isolated torching	
8/25			torching, isolated passive/ dependent crown fire	
8/26			flame length 6" to 2' burning in jackpot fuels, max ROS = 20ft/hr, torching, short-range spotting	
8/27	139	226	short dependent crown fire runs, 80' flame lengths, spotting across Pelican Creek, backing ROS = 15-35 ft/24hr	0.39
8/28	15	241	isolated torching, short-range spotting	0.95
8/29			inactive, smoldering in heavy fuels	
8/30			fire growth observed on main fire and spot fire	
8/31	907	1149	crowning, torching, and spotting runs with moderate surface spread to NE, still active in jackpots in the evening	1.64
9/1			pockets of activity, no significant growth	
9/2			minimal growth	
9/3			little to no growth, jackpots within perimeter	
9/4	264	1412	moderate to intense burning, most activity occurred within perimeter, 1 moderate run in NE corner	0.13
9/5			minimal activity, no growth	
9/6			little or no fire activity	
9/7			no fire growth	
9/8			smoldering	
9/9			burning in heavy fuels with minimal spread	
9/10			burning in heavy fuels, minimal fire growth	
9/11				
9/12			light smoke observed from Lake Ranger Station	
9/13	112	1524	minimal fire activity, no growth	0.66
9/14 TO 10/28			no fire growth	
10/28		1524	Fire declared out	

[a] Acres recorded from perimeter mapping efforts.

[b] Observations from fire monitor narratives

[c] ROS estimates based on 24-hour time period times number of days since previous perimeter

5.2.3 1996 LOST CREEK FIRE

The Lost Creek Fire was ignited on August 28 in the Lost Creek drainage south of the Tower Ranger Station and Roosevelt developed area. This fire was originally managed under the PNF program, but due to potential threat to the developed area, was declared a wildfire at 1800 on August 30 and was controlled by 0630 on August 31.

Vegetation in the area was a mosaic of lodgepole pine (fuel model 8) and Douglas-fir stands (fuel model 2) and non-forest grasslands (fuel models 1 and 2). Although the fire report identified the ignition in fuel model 10, the fuels map indicates the area to be primarily fuel model 8 with very little fuel model 10 in represented. The fire report noted on August 29 that surface fuels were "still very green and showing no ability to support fire growth" with fire spread only in and adjacent to large diameter dead and down materiel. This was similar to the fire activity exhibited by the Coyote and Pelican fires during that burn period.

Since the Lost Creek fire was suppressed at 2 acres, there are no perimeter maps nor observed fire activity for the period of interest. Fire behavior is assumed to have been similar to that experienced on the nearby Coyote PNF. Both the Pelican and Coyote fires exhibited active fire behavior during the period between August 31 and September 2, with the Coyote fire experiencing daily perimeter growth through September 4. The Coyote fire continued to grow through September 12, but fire activity was generally less intense and perimeter growth less significant. Fire behavior projections will include the period of active fire spread on the Coyote fire, August 31 through September 4, as well as the period through the end of the active fire season for the Coyote and Pelican fires, August 31 to September 11.

6.0 RESULTS

6.1 CALIBRATION

Initial calibration for each perimeter were calculated using the BEHAVE estimated ROS comparison, then readjusted within simulations for a better fit. Table 6.1 includes only those used for the simulations described in this study. For the simulations used in this study, adjustment factors for the grass fuel models (FM 1 and FM 2) tend to remain below 0.1. Fuel model 5 adjustment factors also tended to remain low, ranging between 0.03 and 0.20, while those for fuel model 10 varied between less that 0.1 to greater than 0.5. The adjustment factors used for fuel model 8 in this study varied widely from less than 0.2 to greater than 3.0.

Table 6.1 Fuel model ROS adjustment factors used in this study.

Fire	Simulation	FM 1	FM 2	FM 5	FM 8	FM 10
Robinson	9/10 - 9/16	0.02	0.04	0.04	0.72	0.16
Robinson	9/23 - 9/28	0.03	0.08	0.10	1.54	0.34
Robinson	9/10 - 9/12	0.03	0.08	0.08	1.63	0.27
Robinson	9/11 4-hr	0.03	0.03	0.05	2.40	0.34
Raven	8/12 - 8/30	0.01	0.05	0.05	1.25	0.50
Raven	8/21 - 8/23	0.01	0.02	0.04	1.10	0.09
Raven	8/23 - 8/26	0.01	0.01	0.03	0.21	0.06
Raven	8/27 12-hr	0.06	0.16	0.34	3.09	0.77
Tern	8/6 - 8/20	0.02	0.05	0.12	1.04	0.26
Tern	8/20 - 8/27	0.02	0.05	0.08	1.26	0.25
Tern	8/21 - 8/24	0.02	0.05	0.11	1.14	0.25
Tern	8/27 12-hr	0.02	0.05	0.12	1.04	0.26
Coyote	8/31 - 9/12	0.06	0.07	0.08	0.42	0.09
Coyote	8/31 - 9/4	0.04	0.06	0.06	0.34	0.06
Coyote	9/2 - 9/4	0.11	0.13	0.18	0.73	0.16
Coyote	9/4 12-hr	0.22	0.22	0.26	1.41	0.23
Pelican	8/28 - 9/4	0.01	0.02	0.09	0.70	0.10
Pelican	8/24 - 8/27	0.01	0.03	0.13	0.65	0.13
Pelican	8/27 - 8/28	0.01	0.01	0.04	0.16	0.04
Pelican	9/1 8-hr	0.20	0.05	0.20	0.81	0.23

6.2 SIMULATION RESULTS

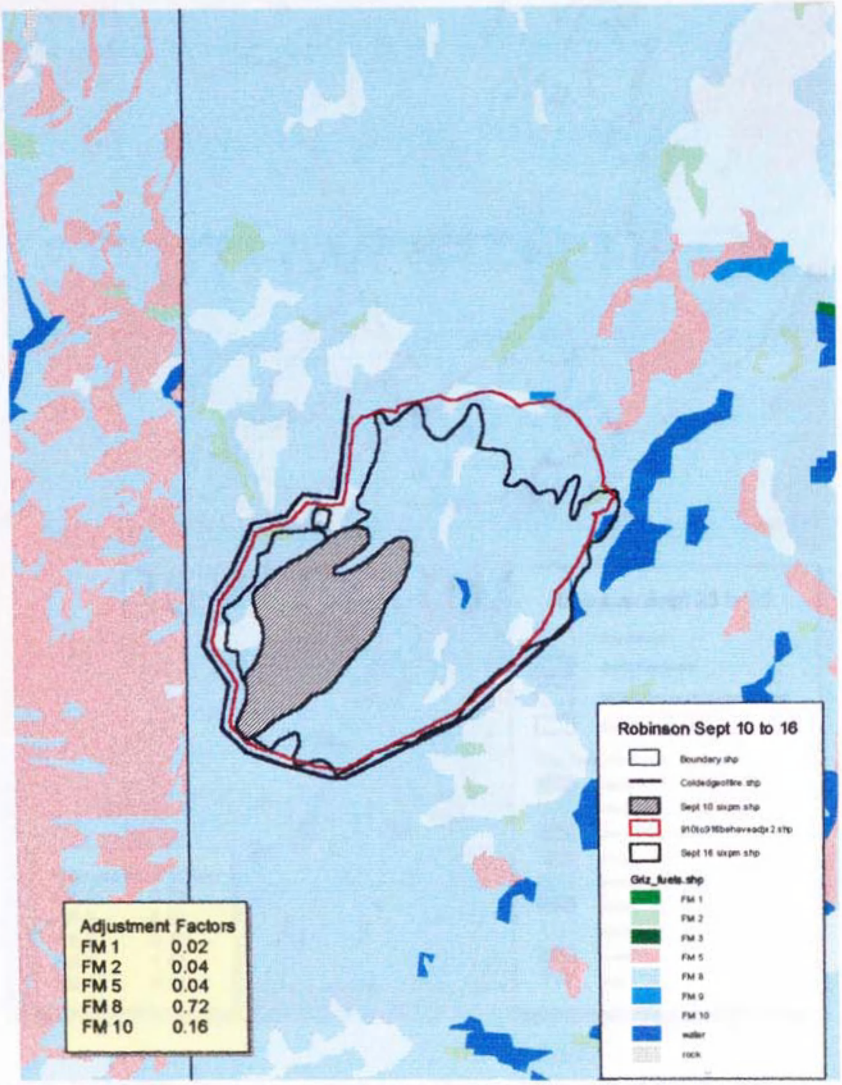


Figure 6.1 FARSITE simulation output over observed fire spread for the Robinson Fire, September 10 to September 16.

Table 6.2 Comparison of acres by fuel model for the Robinson Fire, September 10 to September 16.

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	0	0
2	8	0	1
5	0	0	0
8	1304	45	232
10	80	3	14
Water	5	5	0
Rock	0	0	0
Total acres	1397	53	247

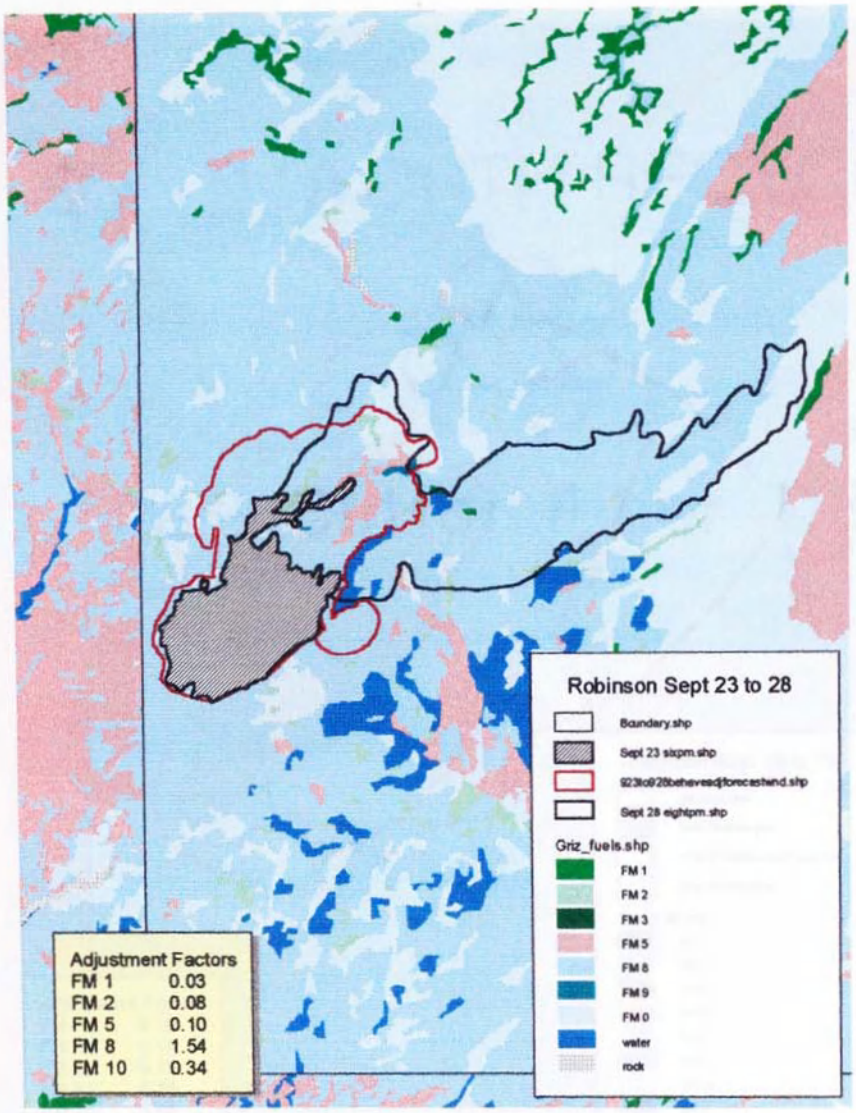


Figure 6.2 FARSITE simulation output over observed fire spread for the Robinson Fire, September 23 to September 28.

Table 6.3 Comparison of acres by fuel model for the Robinson Fire, September 23 to September 28.

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	13	0
2	105	43	17
5	186	7	0
8	1236	3777	1159
9	26	1	11
10	227	627	161
Water	2	187	2
Rock	0	0	0
Total acres	1782	4655	1350

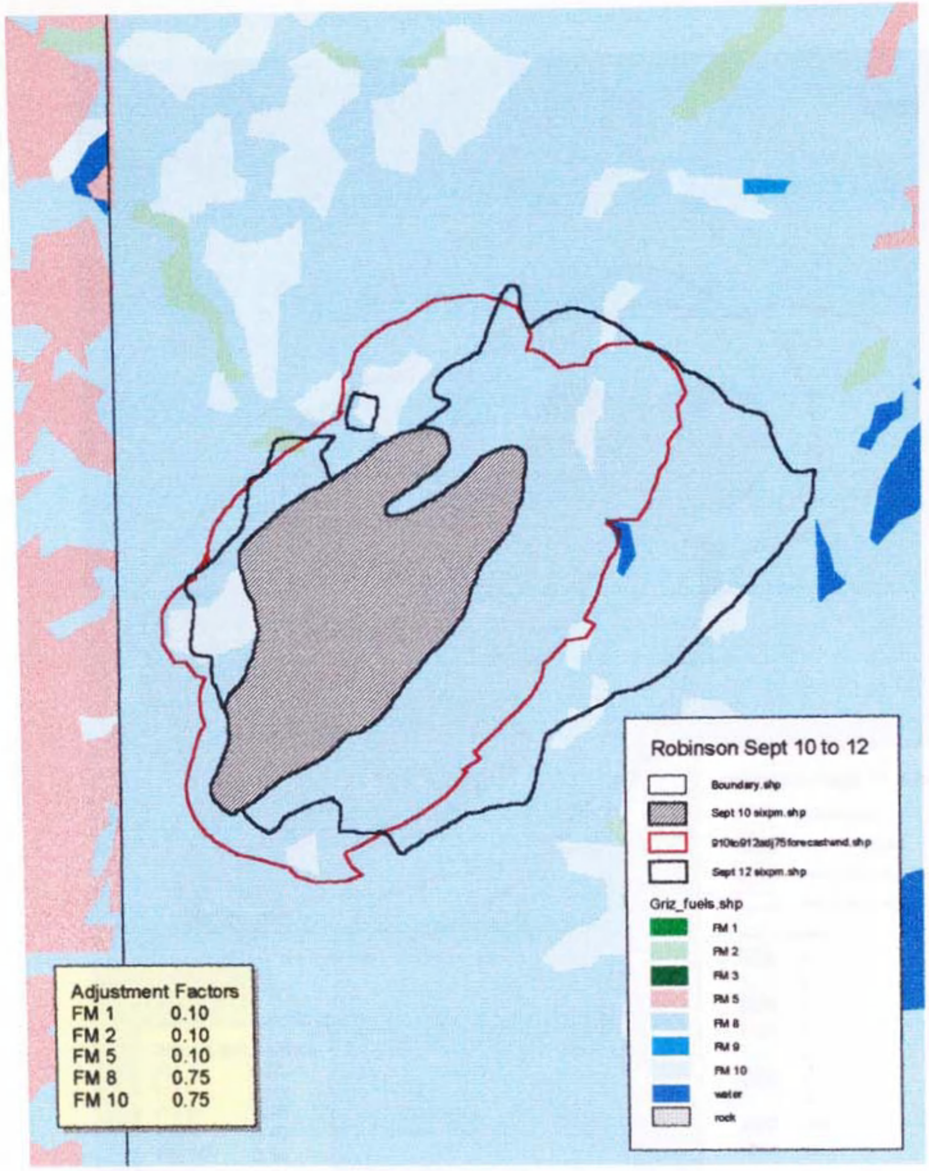


Figure 6.3 FARSITE simulation output over observed fire spread for the Robinson Fire, September 10 to September 12.

Table 6.4 Comparison of acres by fuel model for the Robinson Fire, September 10 to September 12.

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	0	0
2	3	0	4
5	0	0	0
8	431	943	764
10	39	31	53
Water	0	5	0
Rock	0	0	0
Total acres	473	979	821

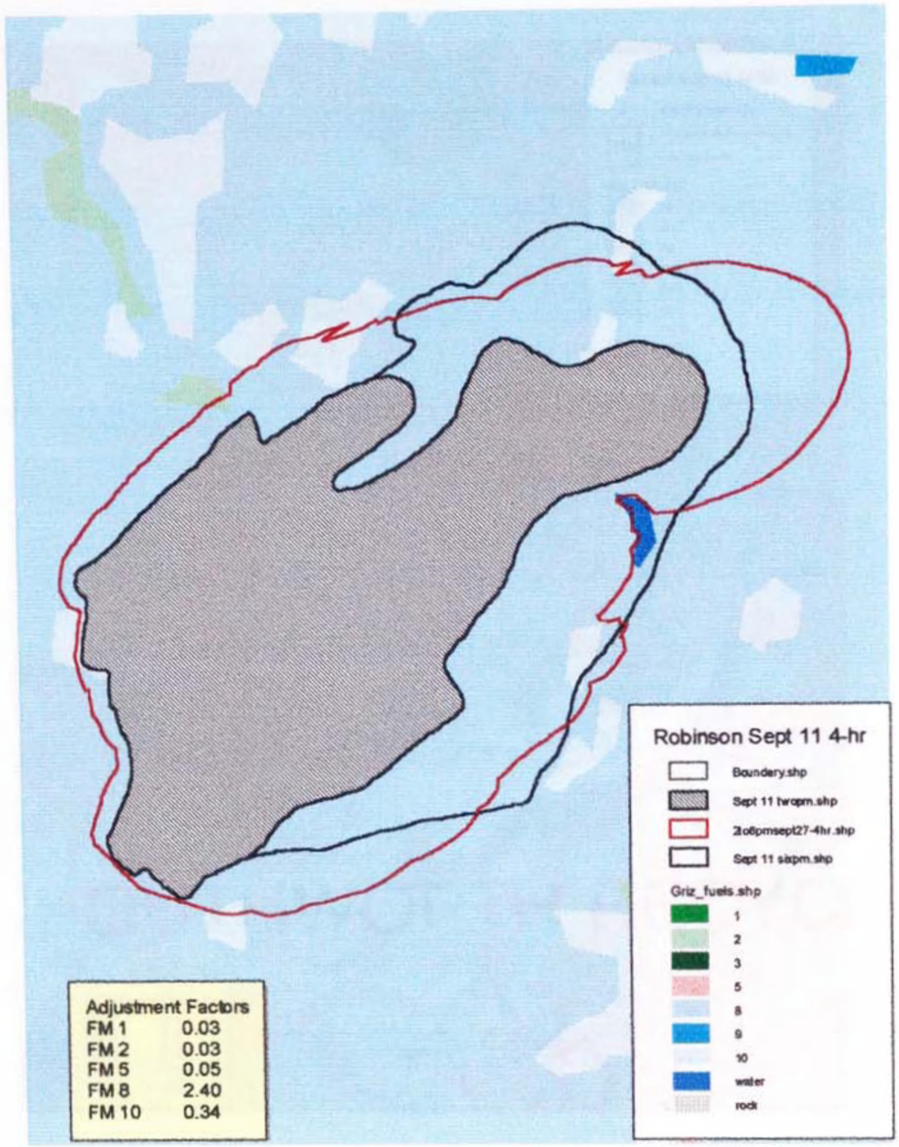


Figure 6.4 FARSITE simulation output over observed fire spread for the Robinson Fire, September 11, 1400 to 1800.

Table 6.5 Comparison of acres by fuel model for the Robinson Fire, September 11 (4-hour).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	0	0
2	0	0	1
5	0	0	0
8	338	45	232
10	9	3	14
Water	0	5	0
Rock	0	0	0
Total acres	347	53	247

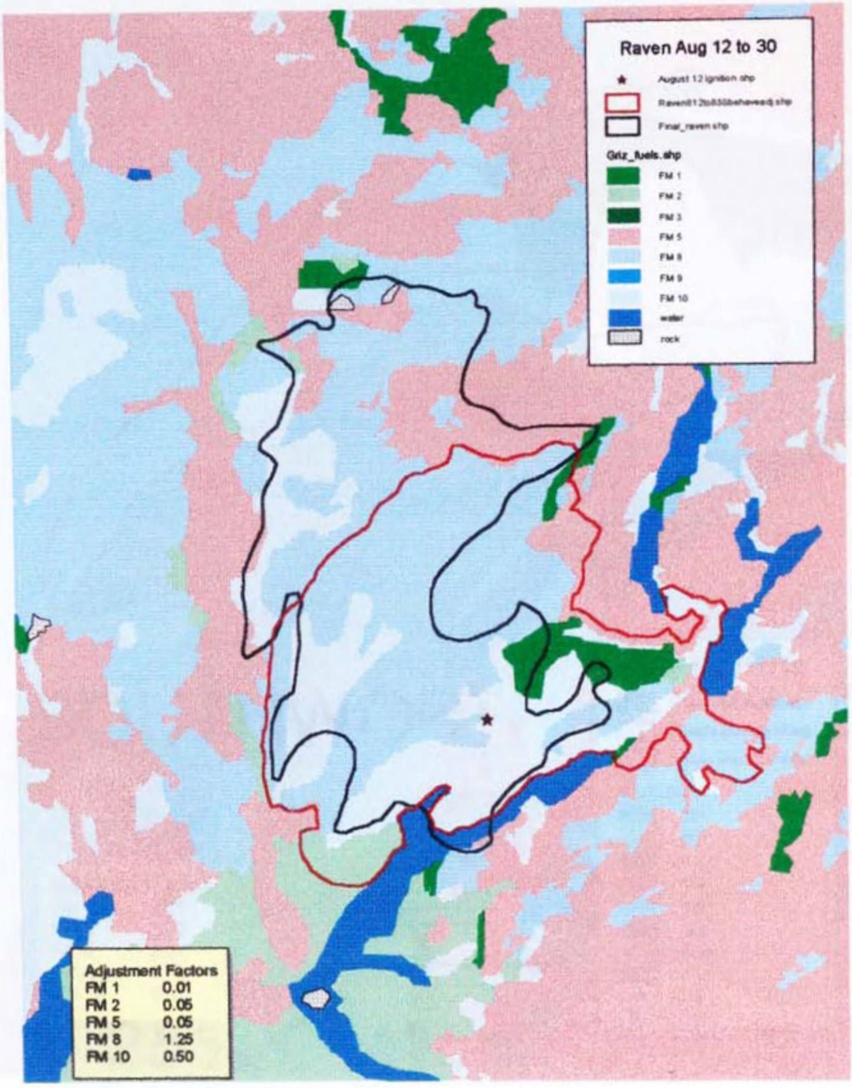


Figure 6.5 FARSITE simulation output over observed fire spread for the Raven Fire, August 12 ignition to August 30.

Table 6.6 Comparison of acres by fuel model for the Raven Fire, August 12 to August 30 (18-day).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	60	11	161
2	0	11	142
5	13	449	249
8	1205	792	731
10	725	252	365
Water	2	38	4
Rock	0	14	0
Total acres	2005	1567	1652

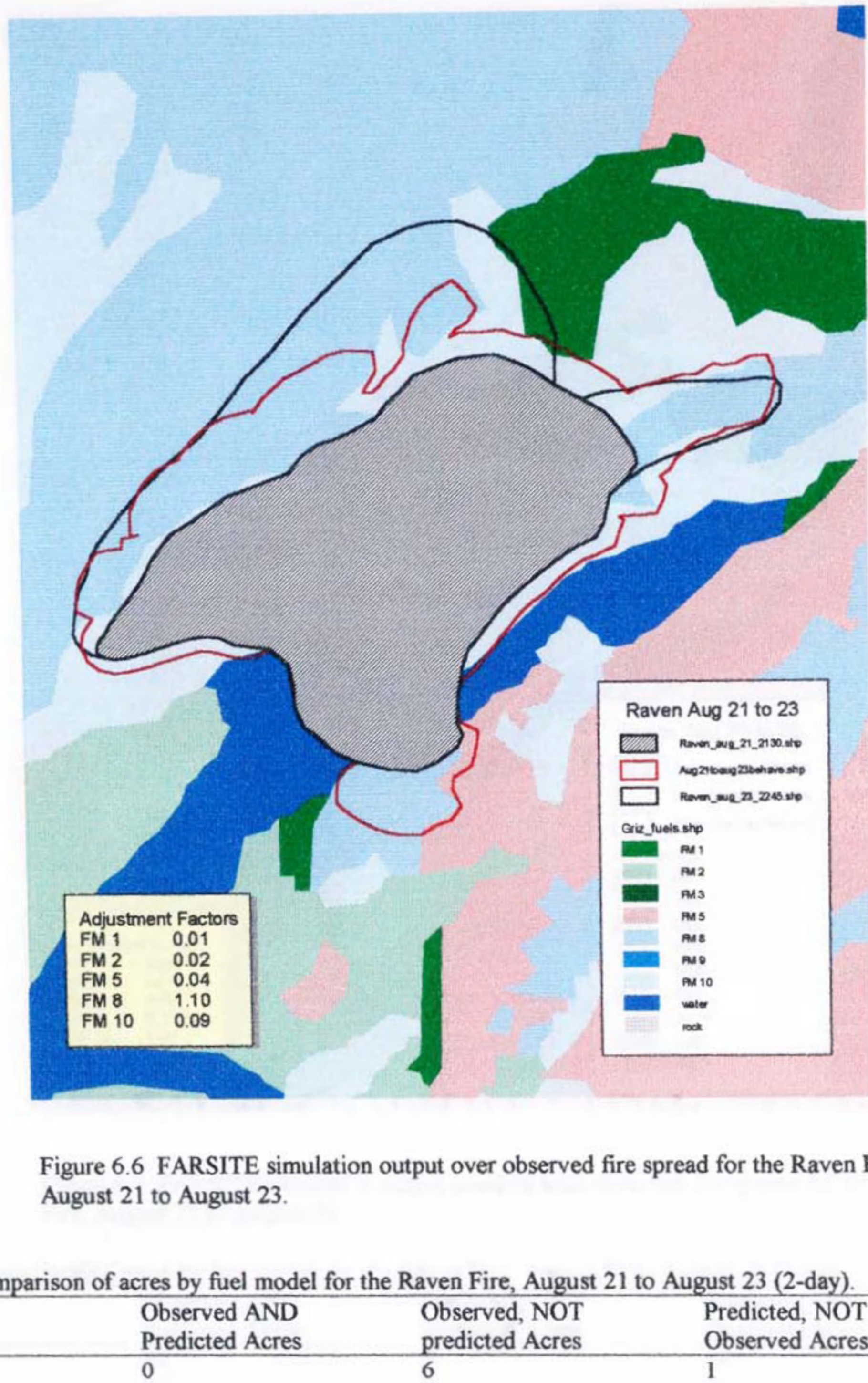


Figure 6.6 FARSITE simulation output over observed fire spread for the Raven Fire, August 21 to August 23.

Table 6.7 Comparison of acres by fuel model for the Raven Fire, August 21 to August 23 (2-day).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	6	1
2	0	0	0
5	0	0	5
8	124	39	34
10	44	24	41
Water	0	0	0
Rock	0	0	0
Total acres	168	69	82

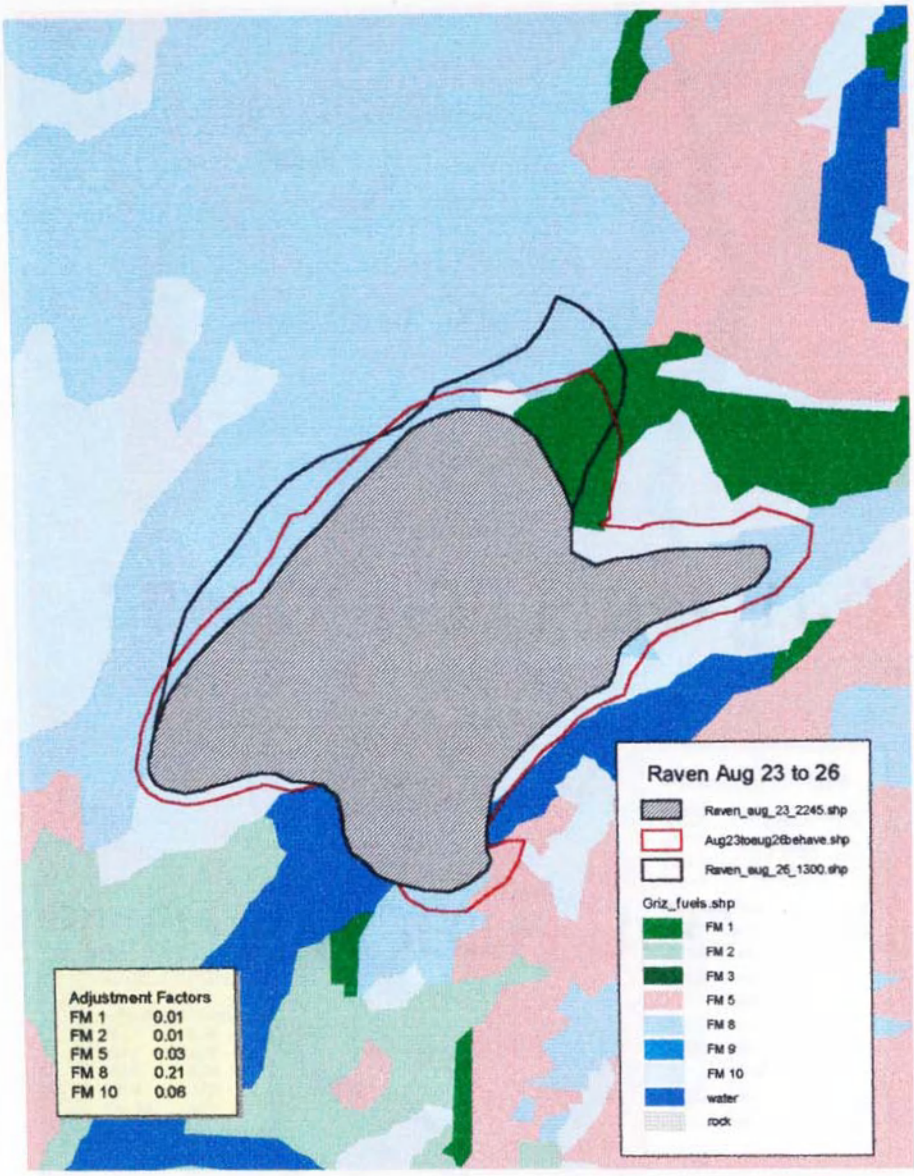


Figure 6.7 FARSITE simulation output overlaid with observed fire spread for the Raven Fire, August 23 to August 26.

Table 6.8 Comparison of acres by fuel model for the Raven Fire, August 23 to August 26 (3-day).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	35	7	15
2	0	0	0
5	0	0	7
8	286	75	298
10	449	2	65
Water	0	0	1
Rock	0	0	0
Total acres	770	84	386

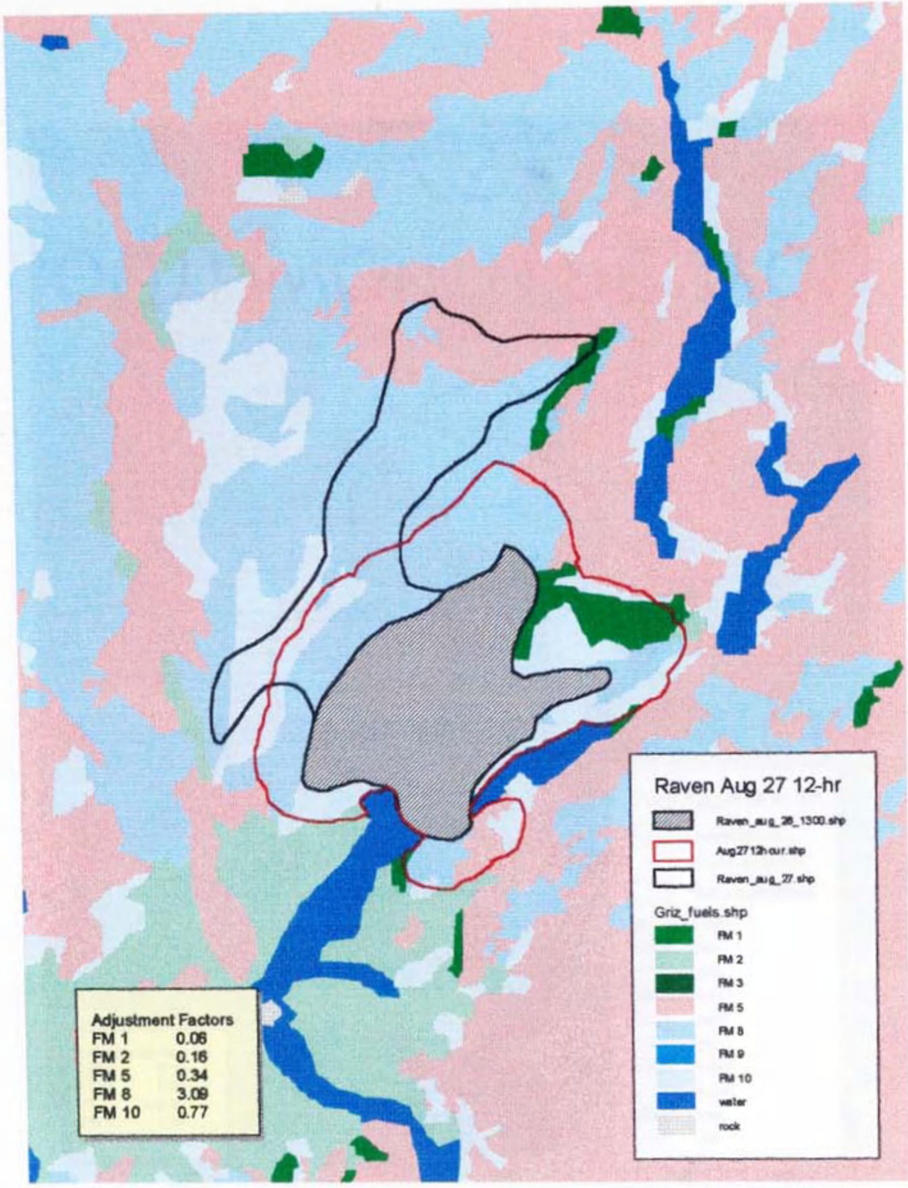


Figure 6.8 FARSITE simulation output overlaid with observed fire spread for the Raven Fire, August 27 0800 to 2000.

Table 6.9 Comparison of acres by fuel model for the Raven Fire, August 27 (12-hour).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	5	141
2	0	0	14
5	0	171	81
8	186	490	462
10	53	90	294
Water	0	0	5
Rock	0	0	0
Total acres	239	756	997

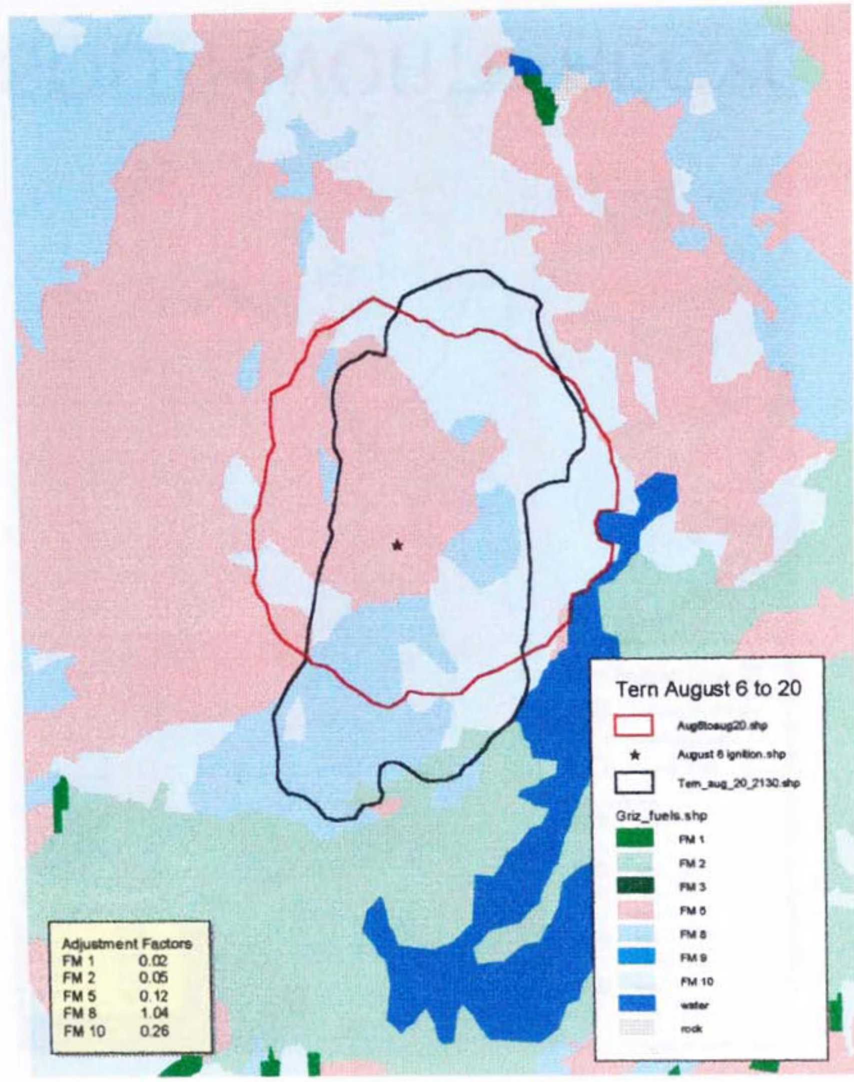


Figure 6.9 FARSITE simulation output over observed fire spread for the Tern Fire, August 6 ignition to August 20.

Table 6.10 Comparison of acres by fuel model for the Tern Fire, August 6 to August 20.

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	0	0
2	0	35	0
5	415	1	219
8	205	224	17
10	456	176	242
Water	0	1	1
Rock	0	0	0
Total acres	1076	437	479

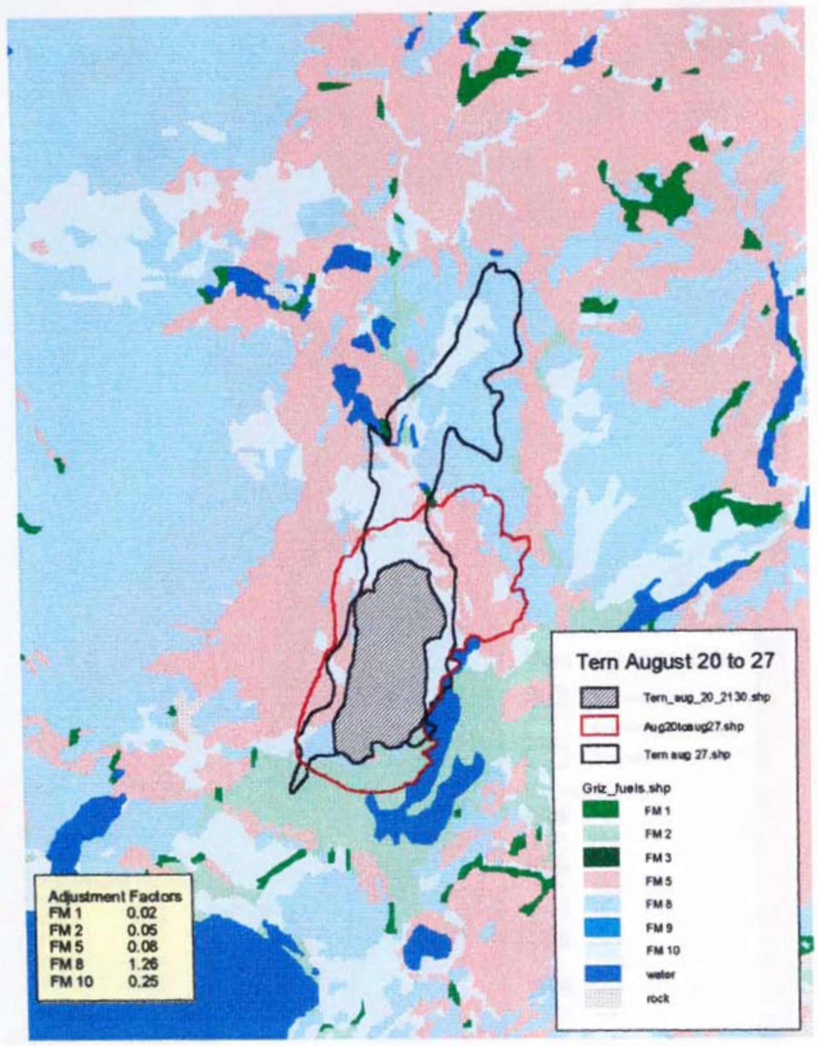


Figure 6.10 FARSITE simulation output over observed fire spread for the Tern Fire, August 20 to August 27.

Table 6.11 Comparison of acres by fuel model for the Tern Fire, August 20 to August 27 (7-day).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	9	3
2	27	59	358
5	296	106	933
8	105	1039	304
10	586	619	242
Water	0	62	4
Rock	0	0	0
Total acres	1014	1894	1844

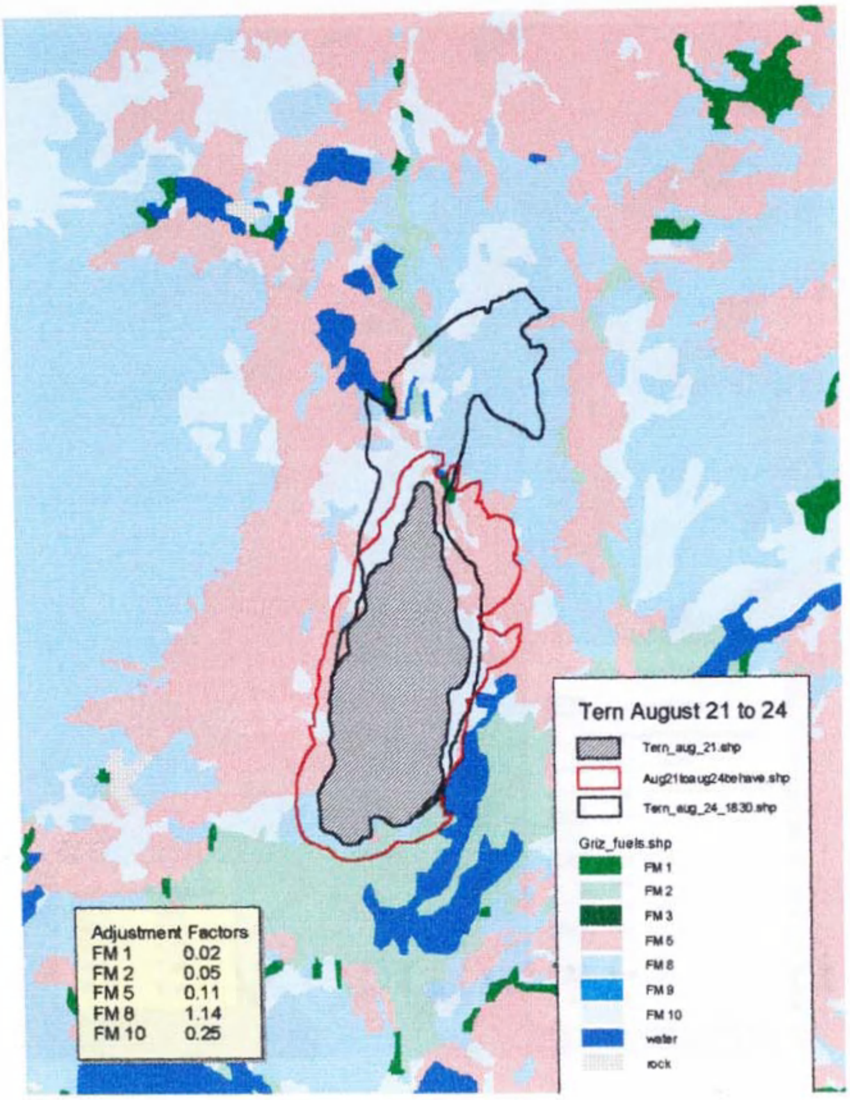


Figure 6.11 FARSITE simulation output over observed fire spread for the Tern Fire, August 21 to August 24.

Table 6.12 Comparison of acres by fuel model for the Tern Fire, August 21 to August 24 (3-day).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	6	3	8
2	5	30	115
5	142	78	527
8	16	702	120
10	325	340	136
Water	2	36	2
Rock	0	0	2
Total acres	496	1189	910

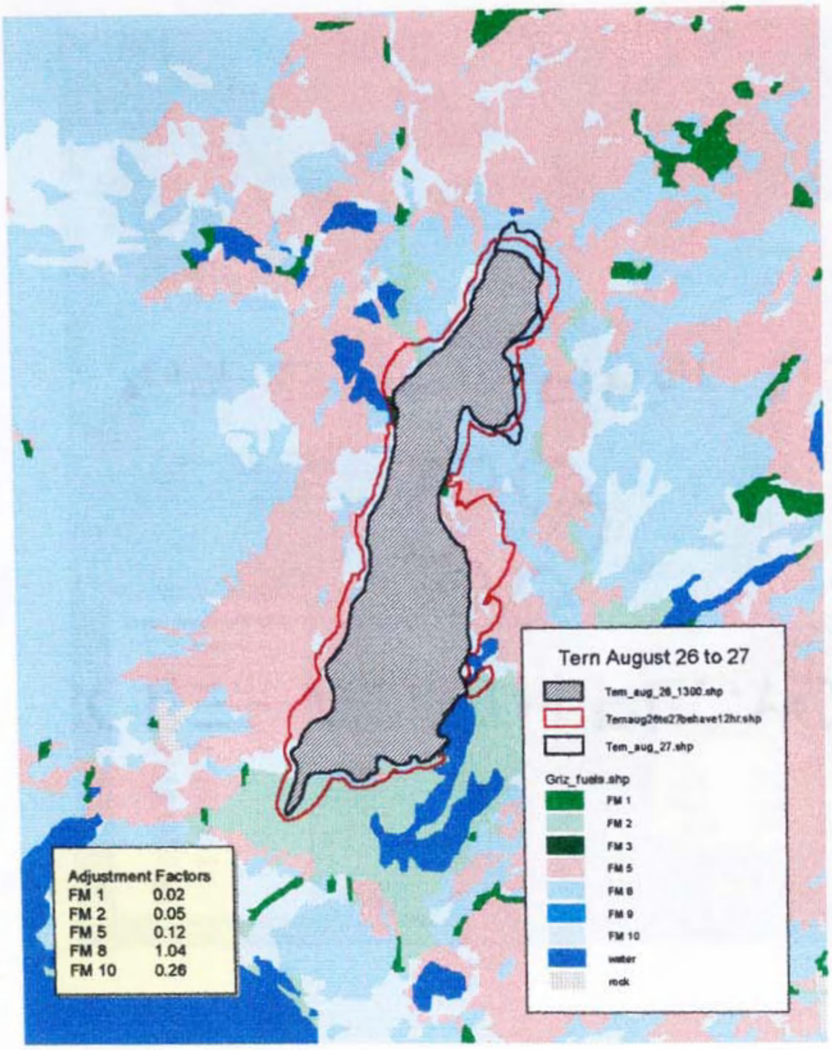


Figure 6.12 FARSITE simulation output over observed fire spread for the Tern Fire, August 27, 0800 to 2000.

Table 6.13 Comparison of acres by fuel model for the Tern Fire, August 27 (12-hour)

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	0	18
2	0	0	199
5	0	0	767
8	120	184	429
10	0	0	287
Water	0	0	4
Rock	0	0	0
Total acres	120	184	1704

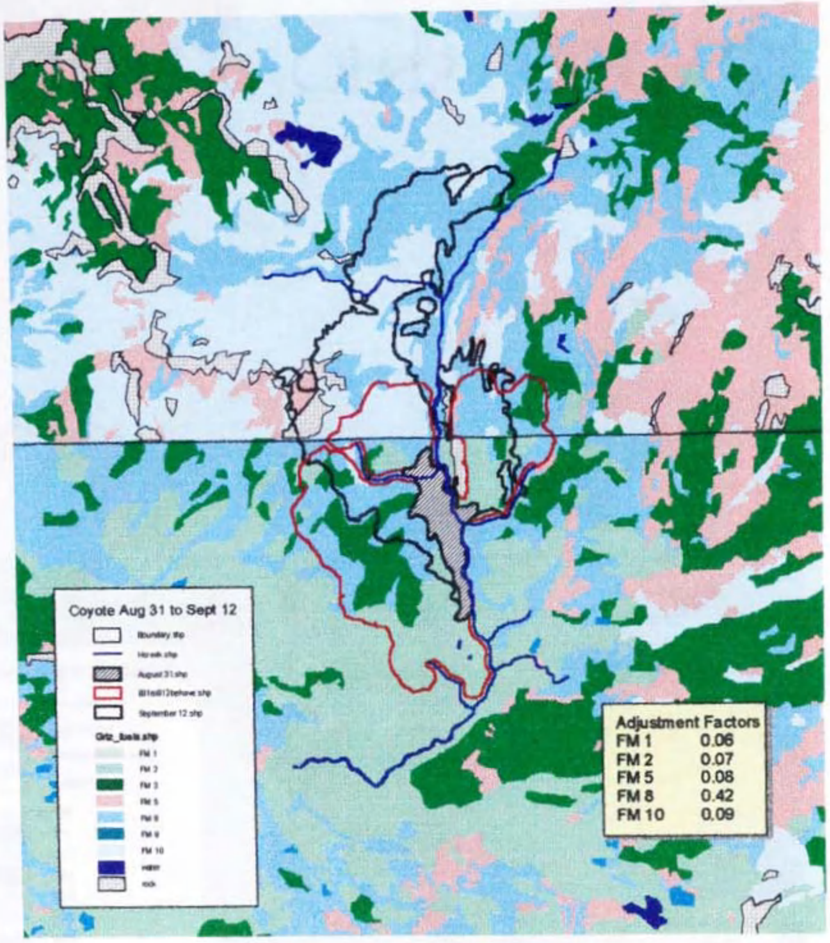


Figure 6.13 FARSITE simulation output over observed fire spread for the Coyote PNF, August 31 to September 12.

Table 6.14 Comparison of acres by fuel model for the Coyote PNF, August 31 to September 12.

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	164	17	584
2	357	48	799
5	20	52	1
8	704	989	594
10	369	934	7
Water	4	215	0
Rock	0	4	0
Total acres	1618	2259	1985

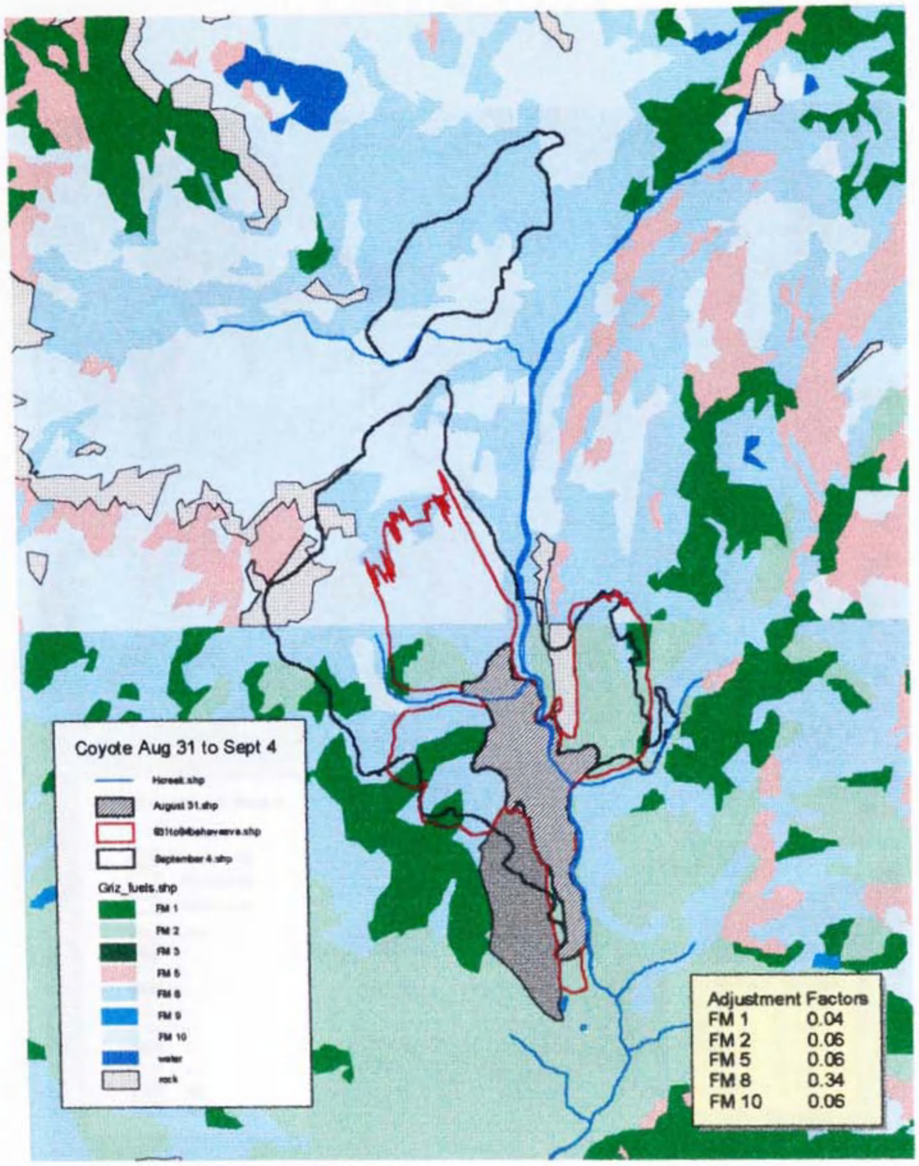


Figure 6.14 FARSITE simulation output over observed fire spread for the Coyote PNF, August 31 to September 4.

Table 6.15 Comparison of acres by fuel model for the Coyote PNF, August 31 to September 4.

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	94	58	41
2	281	85	60
5	0	0	0
8	334	755	29
10	282	571	9
Water	0	3	0
Rock	1	144	2
Total acres	992	1616	141

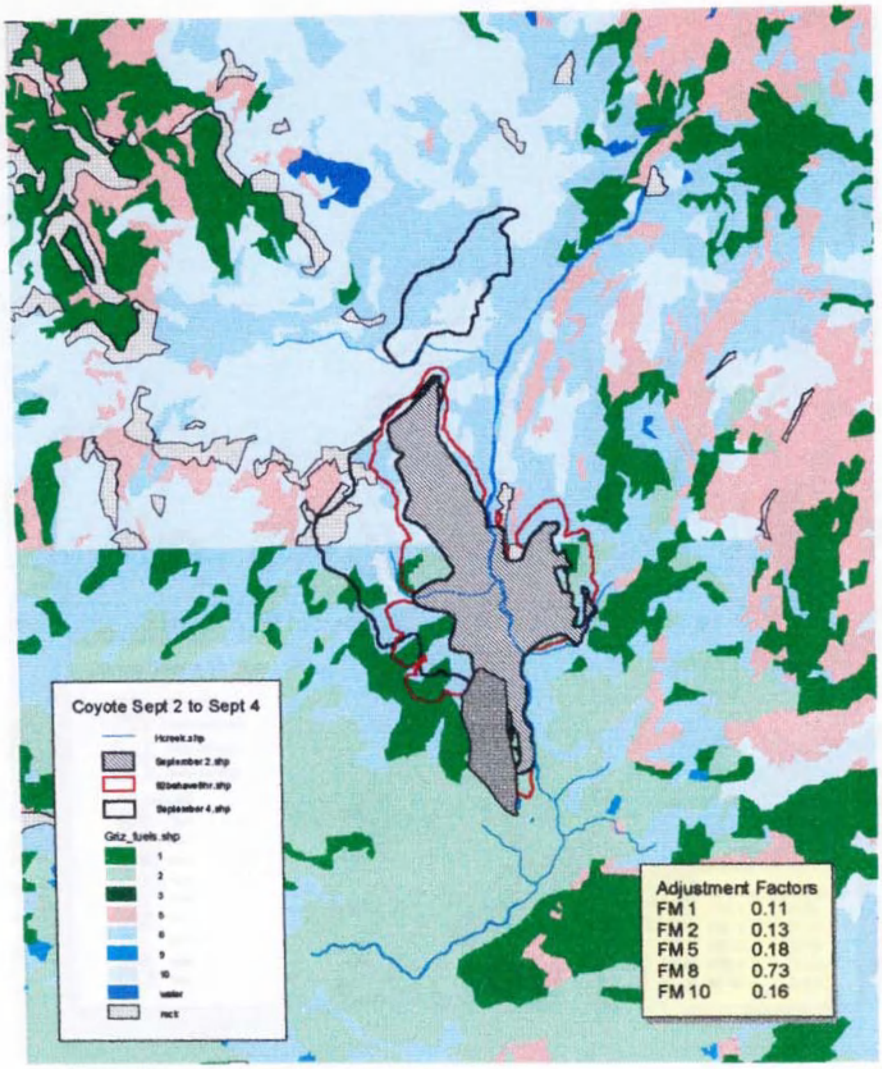


Figure 6.15 FARSITE simulation output overlaid with observed fire spread for the Coyote PNF, September 2 to September 4.

Table 6.16 Comparison of acres by fuel model for the Coyote PNF, September 2 to September 4

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	76	47	100
2	80	41	97
5	0	0	0
8	231	524	178
10	87	385	49
Water	0	0	0
rock	0	92	1
Total acres	474	1089	425

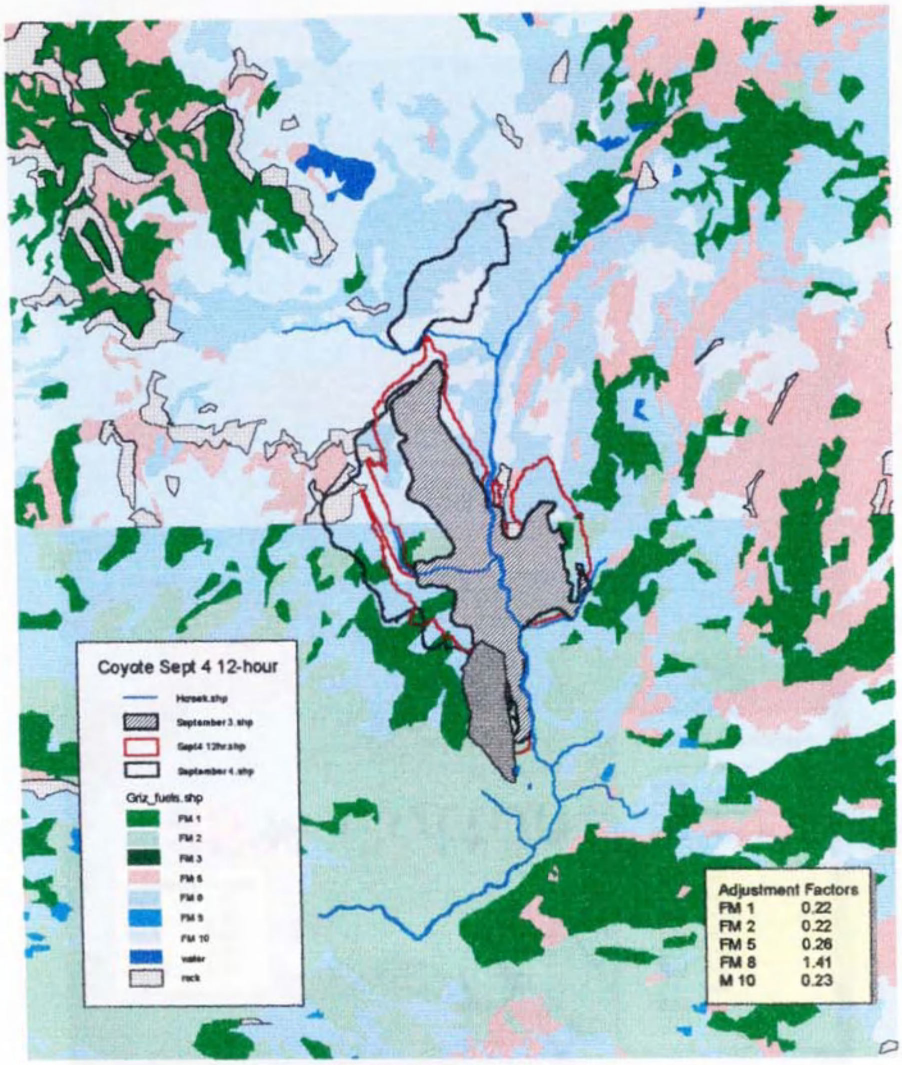


Figure 6.16 FARSITE simulation output over observed fire spread for the Coyote fire, September 4 0800 to 2000 (12-hour).

Table 6.17 Comparison of acres by fuel model for the Coyote PNF, September 4 (12-hour).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	67	56	32
2	69	42	86
5	0	0	2
8	205	537	215
10	170	285	104
Water	0	0	0
Rock	0	92	0
Total acres	511	1012	439

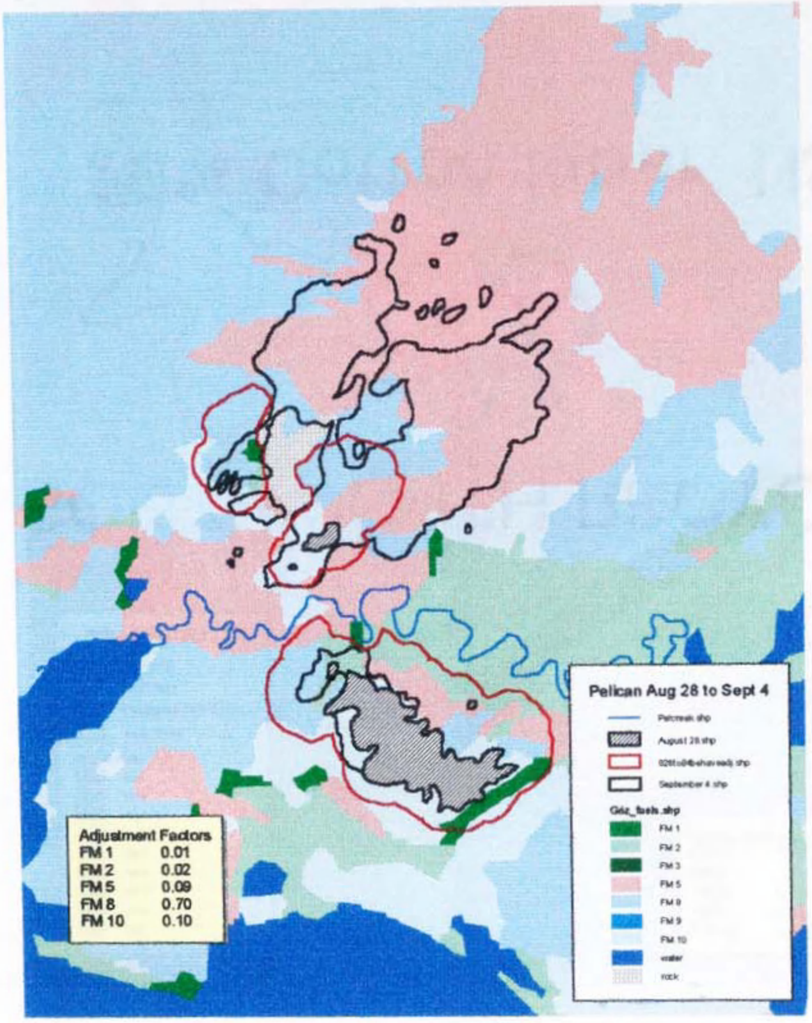


Figure 6.17 FARSITE simulation output over observed fire spread for the Pelican PNF, August 28 to September 4.

Table 6.18 Comparison of acres by fuel model for the Pelican PNF, August 28 to September 4 (7-day).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	8	0	37
2	24	0	105
5	68	584	132
8	102	144	227
10	106	23	151
Water	0	0	0
Rock	0	12	0
Total acres	308	763	652

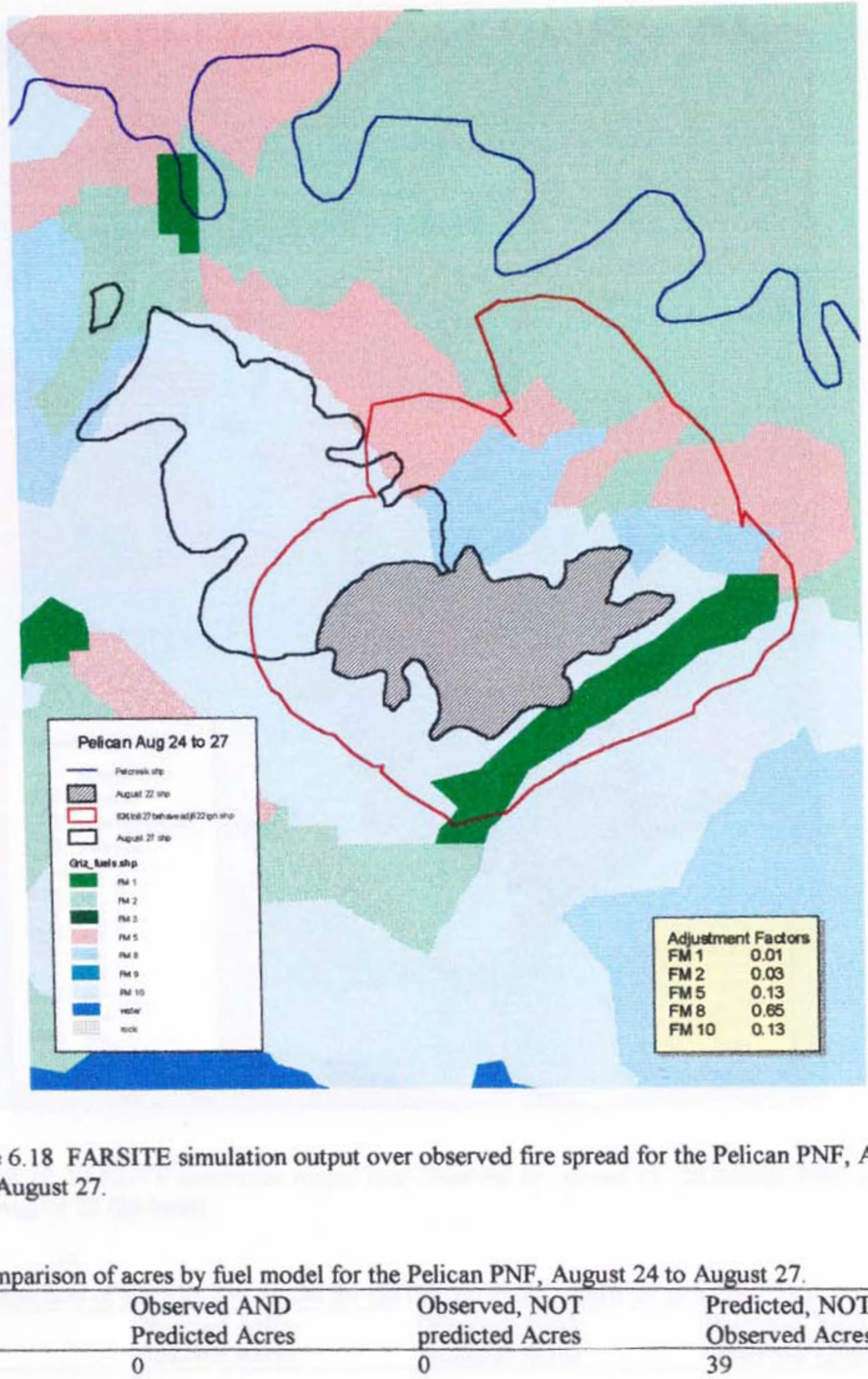


Figure 6.18 FARSITE simulation output over observed fire spread for the Pelican PNF, August 24 to August 27.

Table 6.19 Comparison of acres by fuel model for the Pelican PNF, August 24 to August 27.

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	0	39
2	0	2	44
5	1	0	52
8	3	1	47
10	36	95	90
Water	0	0	0
Rock	0	0	0
Total acres	40	98	272

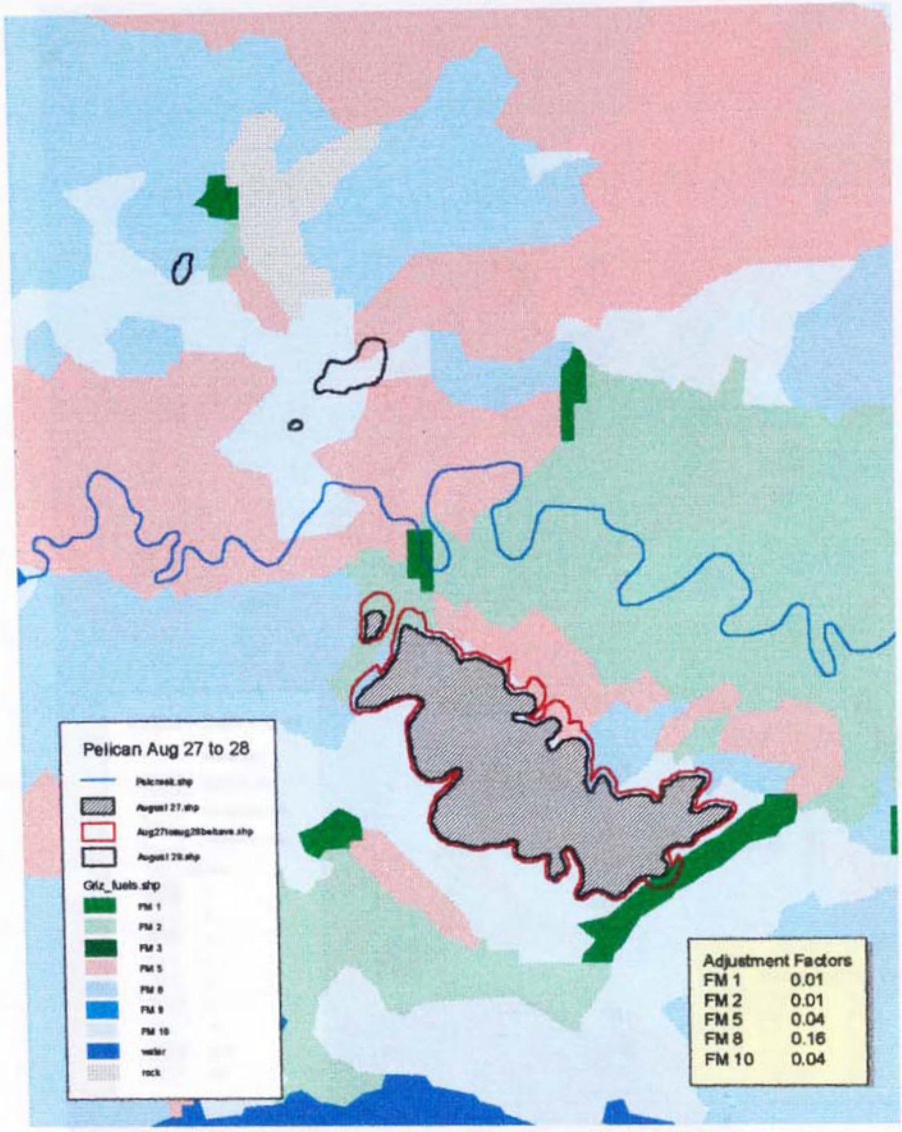


Figure 6.19 FARSITE simulation output over observed fire spread for the Pelican PNF, August 27 to August 28 (24-hour).

Table 6.20 Comparison of acres by fuel model for the Pelican PNF, August 27 to August 28 (24-hour).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	0	3
2	0	0	8
5	0	3	7
8	0	2	8
10	0	10	25
Water	0	0	0
Rock	0	0	0
Total acres	0	15	51

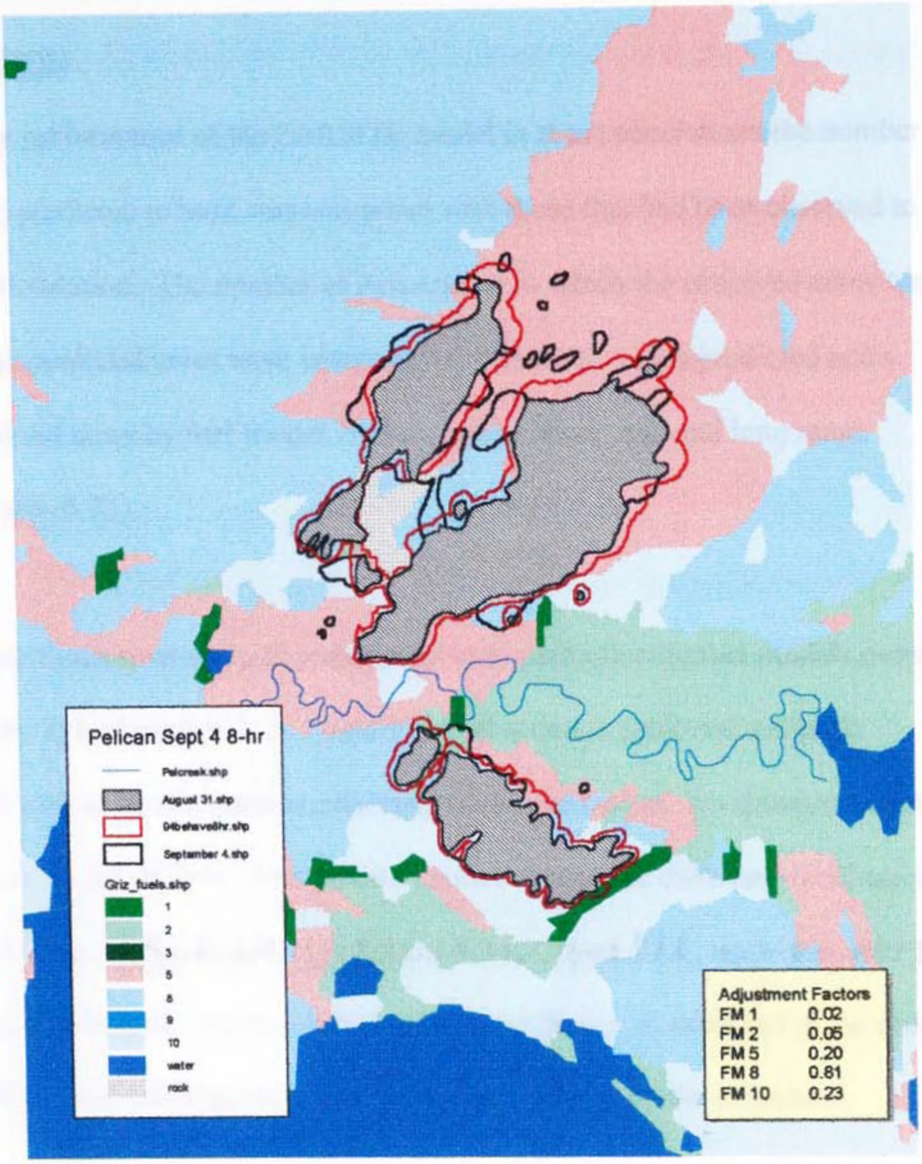


Figure 6.20 FARSITE simulation output overlaid with observed fire spread for the Pelican PNF, September 4 1200 to 2000 (8-hour).

Table 6.21 Comparison of acres by fuel model for the Pelican PNF, September 4 (8-hour).

Fuel Model	Observed AND Predicted Acres	Observed, NOT predicted Acres	Predicted, NOT Observed Acres
1	0	3	1
2	7	12	8
5	78	199	63
8	25	74	50
10	13	60	14
Water	0	0	4
Rock	0	0	0
Total acres	123	348	0

6.3 VALIDATION

To evaluate the performance of the FARSITE model in these simulations the number of acres that were predicted to burn was compared with those that had been observed to burn for each simulation. The number of simulations in which the observed acres were greater than the predicted acres were compared with those in which predicted acres exceeded observed acres by fuel model, by fire, and by short, mid and long range projections (Table 6.22).

Results of these simulations indicate a pattern of over prediction by fuel models overall and individually in fuel models 1, 2, 5, and 10. Fuel model 8 exhibited a slightly different trend with more simulations exhibiting under prediction. No distinctive pattern is observed over all for all fires. This pattern varies between the different fires from over prediction on the Raven fire to under prediction on the Coyote PNF, while the other 3 fires exhibit a little of both. While a pattern of over prediction is exhibited in the short-range projections, mid and long range projections tend toward under prediction.

Table 6.22 Observed versus predicted acres by fuel model, fire, and simulation duration for 20 simulations. Values reflect the number of simulations which fit each criteria (not all fuel models were present in all simulations.)

Fuel Model	FM 1	FM 2	FM 5	FM 8	FM 10	Total
Observed > Predicted	5	4	6	11	8	34
Observed < Predicted	9	11	7	8	10	45
Total	14	15	13	19	18	79
Fire	**Robinson**	**Raven**	**Tern**	**Coyote**	**Pelican**	**Total**
Observed > Predicted	2	0	2	4	2	10
Observed < Predicted	2	4	2	0	2	10
Total	4	4	4	4	4	20
Duration Period	**Short (<2 days)**		**Mid (2-5 days)**		**Long (>5 days)**	**Total**
Observed > Predicted	2		5		4	11
Observed < Predicted	4		3		2	9
Total	6		8		6	20

To address the spatial location of these acres the measure of agreement, indicated by the overlap of observed and predicted acres, was compared with the measurement of disagreement, indicated by the observed and/or predicted acres that do not overlap. These measures were compared for all simulations between the different fuel models, between the different fires, and between short, mid, and long-range projections (Table 6.23).

Results indicate a pattern of greater acres in disagreement than agreement overall. All fuel models exhibit a pattern of greater disagreement, as do Tern, Coyote, and Pelican fires. The same pattern is observed for short and mid range simulation periods, while no pattern either way is exhibited in the long-range projections.

Table 6.23 Measures of agreement (overlap acres that were observed and predicted to burn) versus disagreement of the FARISTE simulation results for fuel model, fire, and simulation duration. Values reflect the number of simulations which fit each criteria (not all fuel models were present in all simulations.)

Fuel Model	FM 1	FM 2	FM 5	FM 8	FM 10	Total
Agreement > Disagreement	1	2	2	3	4	12
Agreement < Disagreement	14	13	12	16	15	70
Agreement = Disagreement	0	2	1	0	0	3
Total	15	17	15	19	19	85
Fire	Robinson	Raven	Tern	Coyote	Pelican	Total
Agreement > Disagreement	2	3	1	0	0	6
Agreement < Disagreement	2	1	3	4	4	14
Total	4	4	4	4	4	20
Duration Period	Short (<2 days)		Mid (2-5 days)	Long (>5 days)		Total
Agreement > Disagreement	1		2	3		6
Agreement < Disagreement	5		6	3		14
Total	6		8	6		20

The acres that were predicted to burn by FARSITE were compared with the acres that had been observed to burn to test the hypothesis that predicted / observed acres = 1.0, indicating a perfect fit. A two-tailed Student's t-test was used to test this hypothesis for each fuel model. Although mean values for predicted / observed exceeds 1.0 for all fuel models present, indicating a pattern over prediction which appears strongest in fuel models 1, 2 and 5, the difference is not statistically significant at alpha = .05 (Table 6.24). Analysis of Variance on these values indicates no significant difference between the performance of the individual fuel models, given the high variability within each fuel model.

Table 6.24 Comparison of predicted acres / observed acres for 20 simulations in YNP.

Fire	Burn Period	FM 1	FM 2	FM 5	FM 8	FM 10	Total
Robinson	9/10 - 9/16		1 13		1 14	1.13	1 13
Robinson	9/23 - 9/28	0.00	0.82	0.96	0.48	0.45	0.49
Robinson	9/10 - 9/12		2.33		0.87	1.31	0.89
Robinson	9/11 4-hr				1.49	1.92	1.49
Raven	8/12 - 8/30	3.11	12.91	0.57	0.97	1.12	1.02
Raven	8/21 - 8/23	1.19			1.62	1 14	1.35
Raven	8/23 - 8/26	28.20		0.47	0.96	2.43	1.24
Raven	8/27 12-hr	0.17			0.97	1.25	1.05
Tern	8/6 - 8/20		0.00	1.52	0.52	1.10	1.03
Tern	8/20 - 8/27	0.33	4.48	3.06	0.36	0.69	0.98
Tern	8/21 - 8/24	1.56	3.43	3.04	0.19	0.69	0.83
Tern	8/27 12-hr				1.81		6.00
Coyote	8/31 - 9/12	4.13	2.85	0.29	0.77	0.29	0.93
Coyote	8/31 - 9/4	0.89	0.93		0.33	0.34	0.43
Coyote	9/2 - 9/4	1.43	1.46		0.54	0.29	0.58
Coyote	9/4 12-hr	0.80	1.40		0.57	0.60	0.62
Pelican	8/28 - 9/4	5.63	5.38	0.31	1.34	1.99	0.90
Pelican	8/24 - 8/27		22.00	53.00	12.50	0.96	2.26
Pelican	8/27 - 8/28			2.33	4.00	2.50	3.40
Pelican	9/1 8-hr	0.33	0.79	0.51	0.76	0.37	0.56
Mean		3.67	4.28	6.01	1.61	1.08	1.36
Median		1.19	1.90	0.96	0.91	1 10	1.00
Std. deviation		7.56	6.05	15.62	2.69	0.70	1.28
Significance		0.23	0.06	0.31	0.33	0.85	0.23

Blanks indicate that fuel model was not present in either the predicted nor the observed perimeters. A value of zero indicates the presence of that fuel model in the observed acres only.

Table 6.25 Analysis of Variance of predicted / observed acres between fuel models.

ANOVA: Single Factor						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	236.5289	4	59.13224	1 135724	0.346623	2.498921
Within Groups	3748.728	72	52.06567			
Total	3985.257	76				

To address the spatial location of those acres, the overlap of those acres that were predicted to burn as well as observed to burn was evaluated. This overlap was compared with the total acres that were observed to burn for that time period, testing the hypothesis that the overlap / observed acres = 1.0. Results of the one-tailed t-test indicate a significant difference between the overlap acres (or agreement) and the total acres observed to burn for each fuel model and overall, with significance values approaching zero at alpha =.05. Analysis of Variance indicates that all fuel models performed similarly.

Table 6.26 Comparison of acres of overlap between predicted and observed / observed acres for 20 simulations in YNP

Fire	Burn Period	FM 1	FM 2	FM 5	FM 8	FM 10	Total
Robinson	9/10 - 9/16		1.00		0.97	0.96	0.96
Robinson	9/23 - 9/28	0.00	0.71	0.96	0.25	0.27	0.28
Robinson	9/10 - 9/12		1.00		0.31	0.56	0.33
Robinson	9/11 4-hr				0.88	0.75	0.87
Raven	8/12 - 8/30	0.85	0.00	0.03	0.60	0.74	0.56
Raven	8/21 - 8/23	0.83			0.79	1.00	0.90
Raven	8/23 - 8/26	0.00		0.00	0.28	0.37	0.24
Raven	8/27 12-hr	0.00			0.76	0.65	0.71
Tern	8/6 - 8/20		0.00	1.00	0.48	0.72	0.71
Tern	8/20 - 8/27	0.00	0.31	0.74	0.09	0.49	0.35
Tern	8/21 - 8/24	0.67	0.14	0.65	0.02	0.49	0.29
Tern	8/27 12-hr				0.39		0.39
Coyote	8/31 - 9/12	0.91	0.88	0.28	0.42	0.28	0.42
Coyote	8/31 - 9/4	0.62	0.77		0.31	0.33	0.38
Coyote	9/2 - 9/4	0.62	0.66		0.31	0.18	0.30
Coyote	9/4 12-hr	0.54	0.62		0.28	0.37	0.34
Pelican	8/28 - 9/4	1.00	1.00	0.10	0.41	0.82	0.29
Pelican	8/24 - 8/27		0.00	1.00	0.75	0.27	0.29
Pelican	8/27 - 8/28			0.00	0.00	0.00	0.00
Pelican	9/1 8-hr	0.00	0.37	0.28	0.25	0.18	0.26
Mean		0.46	0.53	0.46	0.43	0.50	0.44
Median		0.62	0.64	0.28	0.35	0.49	0.34
Std. deviation		0.40	0.39	0.42	0.28	0.28	0.26
Significance		9.78E-04	1.67E-03	2.24E-03	8.52E-06	2.27E-05	8.50E-06

Blanks indicate that fuel model was not present in either the predicted nor the observed perimeters. A value of zero indicates the presence of that fuel model in the observed acres only.

Table 6.27. Analysis of Variance of Overlap / Observed acres between fuel models.

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.106475	4	0.026618	0.223721	0.924327	2.498921
Within Groups	8.566739	72	0.118982			
Total	8.673214	76				

6.3 1996 LOST CREEK FIRE

Simulation of the Lost Creek fire were run using calibration from the Coyote fire. Fire activity was assumed to concur with that on the Coyote fire due to the proximity of the two fires. Although previous examples (i.e. the Tern and Raven fires) indicate otherwise, it must be assumed that there is some degree of reliability in this assumption in order to make projections. Using the Coyote fire calibration for these burn periods, the predicted growth of the Lost Creek fire reaches 16 acres in the four day periods, August 31 to September 4, and 1,475 acres for the 12-day period, August 31 to September 11.

Due to the limited fire spread of this fire under the Coyote adjustment factors, simulations were also included using no calibration (adjustment factors = 1.00). Total acres under this scenario were 593 for the 4-day simulation, August 31 to September 4, and 3,349 acres for the 11-day simulation, August 31 to September 11. Fire growth in all 4 simulations occurred primarily in fuel models 1 and 8.

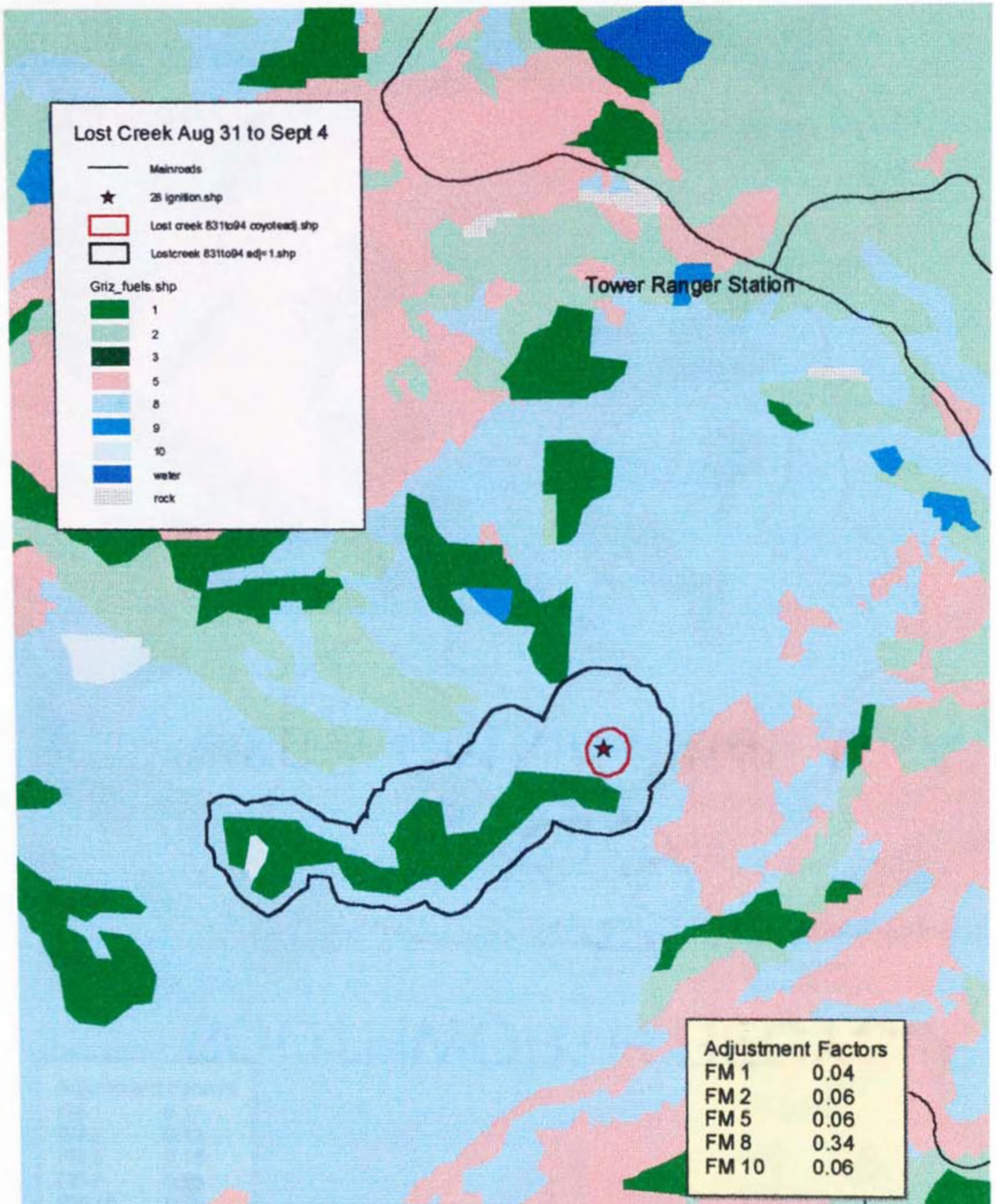


Figure 6.21 Projection of the Lost Creek fire, August 31 to September 4, using both adjustment factors from Coyote PNF calibration and Adjustment factor = 1.0.

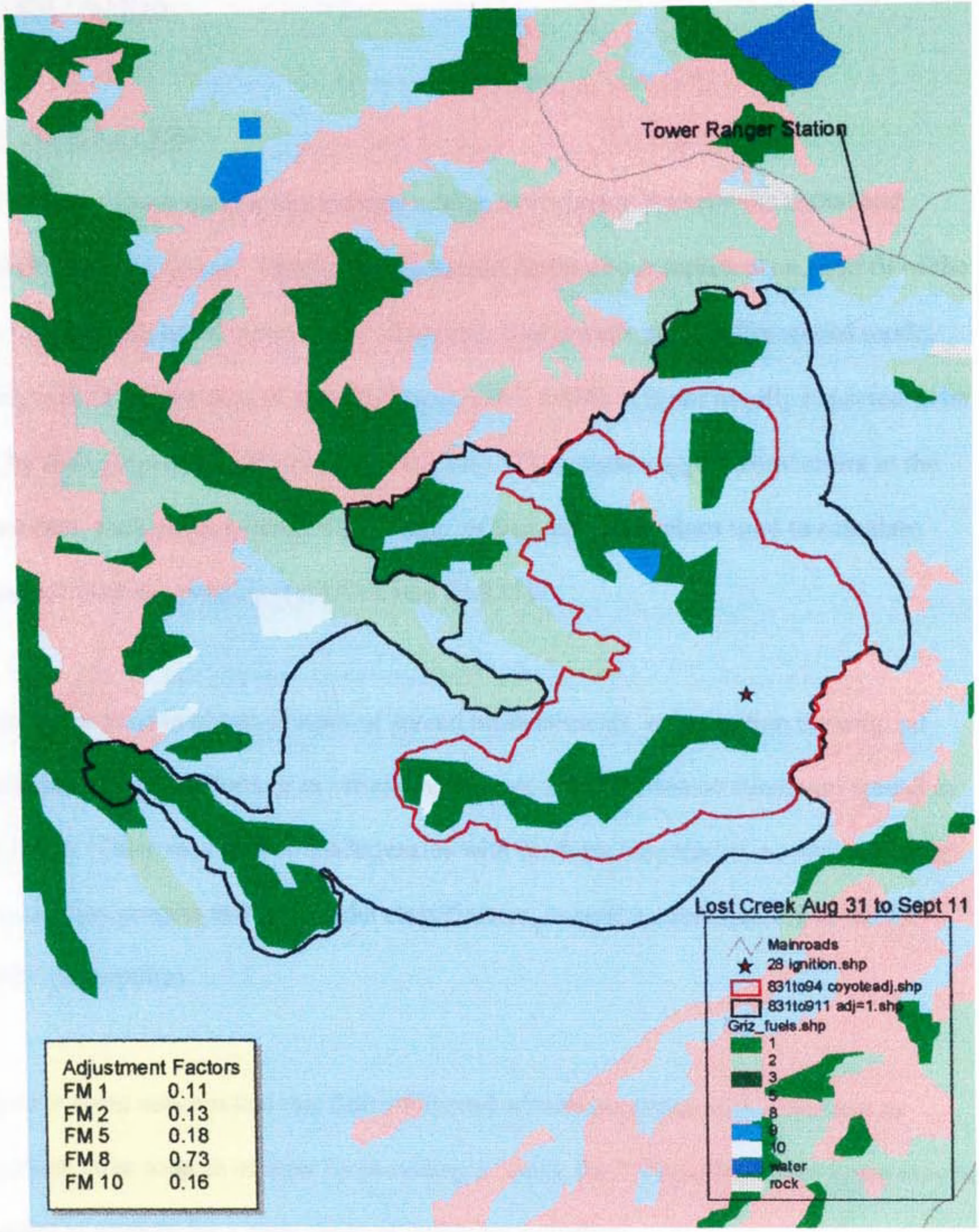


Figure 6.22 Projection of the Lost Creek fire, August 31 to September 11, using both adjustment factors from Coyote PNF calibration and Adjustment factor = 1.0.

7.0 DISCUSSION

7.1 CALIBRATION

All of these adjustment factors indicate a large discrepancy between the actual and expected rates of spread. Ideally, an adjustment factor of 1.0 represents a good fit of the fire behavior models (Finney 1997). Although Rothermel's surface fire spread model tends to over predict rates of spread (Finney 1997, 1998), it is not usually expected to be off by such large factors (Finney pers. comm.). This might suggest some errors in the input data, such as the average wind, slope, or fuel moisture values used to calculate expected rates of spread in BEHAVE and FARSITE.

Errors may exist in observed rates of spread measurements, either within the original perimeter mapping efforts or in estimating the rate and direction of maximum spread in ArcView. There may also be inadequacies with the fuels map due to inconsistencies in the mapping process and fuel model classification, as well as inadequacies in the fuel model descriptions.

There is some concern that this Rate of Spread adjustment factor allows the user to overlook large sources of error by providing a "quick fix." This adjustment factor may be applied to account for a wide range of problems including:

- Inconsistencies in weather data collection (e.g. location of weather observation)
- Spatial variation of winds and weather (e.g. terrain influenced wind patterns)
- Temporal resolution of wind data (e.g. 10-min avg. speeds vs. gust speeds)

- Inconsistencies in fuels data mapping
- Spatial resolution of fuels map / non-uniform fuel arrangement
- Errors within the surface fire or crown fire spread models
- Errors propagated from the fine fuel moisture model
- Other errors or inadequacies within the FARSITE model

Many of these problems involve data collection errors or inconsistencies. Improvements to these various input values should be considered prior to future calibration and validation efforts.

This approach to calibration is very general and overlooks more specific analysis of ROS of the individual fuel models. Only one ROS estimate can be determined for each perimeter, which may encompass multiple fuel models. This may be adequate for the primary fuel model or models present, but overshadows those fuel models that occur only in small patches on the landscape. For example, fuel model 1, representing small open meadows surrounded by timber fuel models 8 or 10, may not have burned due to high fuel moistures. Yet these areas became encompassed within the recorded fire perimeter, which was drawn around the general burned area without incorporating the detail of mosaic pattern of unburned fuels. For this reason, it was determined that insufficient information was available for this study to evaluate fuel models 3 or 9, although a small portion of fuel model 9 occurred within one Robinson Fire simulation.

It was originally thought that during the dates that the Tern and Raven fires overlapped, both fires might be modeled together. However, because the perimeters were not recorded for the same burn periods and adjustment factors varied between the two fires, simulations were not combined.

7.2 VALIDATION

FARSITE validation depends largely upon the accuracy of the input data and the appropriate use of this system as well as the performance of all the individual models. It is important to prioritize the problems in order to proceed with validation. One should first look for errors in the input data, than address user error, and only then can model validation be approached (S493 class notes), as the inaccuracy of the input data undermines the performance of the model.

The results indicate an over prediction of fire spread by the FARSITE fire prediction system. Small adjustment factors of less than 0.1 were required to slow the fire spread in order to more closely match actual fire spread. Ideally, the adjustment factor should be close to 1.0 indicating a close fit to the fire behavior models (Finney 1997). These low values indicate a need for improvement of other input values, such as the fuels map or weather data. The spatial fuels map and the weather data are most subject to error due to mapping constraints and terrain influenced weather, specifically winds, that are not normally captured in observations.

Fuels Map/Spatial Input

Resolution of the landscape file provides one source of error in the resulting fire behavior. The Grizzly Bear Habitat Component map originated as a 30 acre Habitat

Type map (Despain 1977) overlaid by a 5-acre cover type map (Mattson and Despain 1985), which was updated to capture changes resulting from the 1988 fire severity (Despain et al. 1989) at a 50-meter resolution. This was then converted into a 30-meter pixel file for FARSITE, but resolution is still limited primarily by the original 5-acre cover type map. The assumption that fuel conditions remain constant within this resolution provides a potential source of error in fire behavior output.

YNP vegetation cover often occurs in a mosaic pattern with spatial variation at much smaller scales than the map indicates. Significant fuel breaks such as the rock and talus slopes of Hellroaring Mountain were not captured by the Grizzly Bear Habitat mapping effort. The focus of this mapping effort was on the existing vegetation, however sparse. Although the Hellroaring Mountain error is obvious, it is indicative of other less obvious inadequacies with this fuels map.

Although resolution of the landscape file input is important, errors within the existing resolution must be addressed before an increase in the detail would be effective. Obvious inconsistencies in the fuels map include the dramatic changes at the park boundary. The western boundary with the Targhee may actually exhibit this immediate fuel change due to logging practices, the effects of which may be seen via satellite imagery. More typically, however, this is representative of inconsistencies in mapping efforts by the different agencies.

Inconsistencies were noted between observed fire behavior and that associated with fuel model assignments, or descriptions. During the 1996 fires, fire monitors had noted that the grasses (fuel models 1 and 2) were not yet cured out and that fire was not carrying through these fuels. FARSITE simulations, however, allowed fire spread into these areas despite the assigned adjustment factor of 0.01. Fuel model descriptions assume the grasses to be cured out (Anderson 1982) and the ROS adjustment factor must be greater than zero (Finney 1997). Because FARSITE does not allow for an adjustment factor of 0 to prevent any fire spread into these areas, these fuels might be reclassified as non-fuel for periods during which these fuel moistures remain high and adjusted during future simulations as deemed appropriate.

Fuel model 5 has been used by YNP fire management (Renkin pers. comm.) to refer to recently burned areas. This fuel model does not appear to be representative of areas for several years post burn (e.g. LP0 stands). Although, by definition, vegetation recovery in recently burned area may fall under the definition of a fuel model 1, fire behavior does not fit this model. Experience has shown that typically fire does not spread through these areas due to lack of available fuels, so perhaps the best representation of these areas may fall under a non-fuel type until further vegetation recovery occurs.

Large areas across the YNP landscape are represented by fuel model 8. A wider range of adjustment factors was applied to this fuel model than the other fuels, indicating a different problem with fuel model 8. Adjustment factors during several simulations exceeded the 1.0 value for a "good fit" indicating an under prediction in fire behavior, while others remained below 1.0 indicating an over prediction. Perhaps some of these areas have more heterogeneous fuels conditions and would be better described by the fuel model with greater fire behavior, such as fuel model 10 or possibly fuel model 2. Areas represented by the LP0 cover type encompass stand age ranging from 150 to 300 years old. While fuel model 8 may describe the younger stands in this range, the older stands may be more representative of a fuel model 10. Future efforts may be directed at improving this aspect of the existing fuels map.

FARSITE exhibited frequent torching and short-range spotting, leading to occasional passive crown fire runs in areas of fuel model 10. This fire behavior was frequently observed by fire monitors on scene and noted in fire management records for each of these fires. However, there was insufficient data available from these fires to evaluate the location and extent of this type of fire behavior.

The recorded perimeters of actual fire spread drew general polygons around mosaics of burned and unburned fuels. Subsequent fire activity may have occurred within these perimeters by burning up the unburned islands. Current modeling systems do not address this type of burn pattern.

Wind and Weather Input

Fire monitors may collect weather data on site, however, they tend to move around throughout the burn period leading to spatial inconsistencies in both wind and weather values. While one data collection point may have been in the bottom of a canyon, the next may have been mid-slope or on a ridge top. This may be a critical problem in collecting appropriate wind data, which can lead to large errors in direction and rate of spread.

Both the Coyote and Robinson fires exhibited fire behavior influenced by canyon winds. The steep, narrow Hellroaring drainage created localized winds changes and eddies on the Coyote fire, as noted by fire monitors. Eddies in certain locations in the drainage pushed the fire back into itself, preventing further up drainage spread until the fire was able to creep beyond this point and predominant up-canyon winds once-again influenced fire spread.

The Bechler Canyon to the east of the Robinson fire had a significant influence on the prevailing southwesterly winds as they were funneled to the east into the canyon. This is exhibited in the spread pattern of the fire as it headed toward the mouth of the canyon.

Fire monitor notes acknowledged the frequent occurrence of inversions on both the Coyote and Pelican fires. Conditions under an inversion layer tend to dampen fire behavior and delay diurnal pattern of heating and drying until the fog lifts, often not until 11 am or later. This was also noted for the other fires in fire behavior forecasts. It was also noted that occasional nighttime fire activity was exhibited on slopes affected by thermal belts.

Although weather stations may be strategically placed across the landscape, and at a relatively high density within YNP, there is still room for large spatial variation in weather data, particularly wind speed and direction, between these locations. Simulations of the Raven fire exemplify this problem, as the direction of spread differs from the observed direction of spread. This creates a problem in trying to predict fire behavior of an ongoing fire and is a likely factor to consider when interpreting the Lost Creek Fire simulations.

Once the user is relatively confident that these data errors are minimized, one must ensure that the user is handling the FARSITE model correctly (e.g. input parameters) and applying this system in an appropriate manner. For instance, due to the 30-meter resolution of the input layers in FARSITE, it is inappropriate to apply this model to small fires that do not experience fire growth. FARSITE does not predict "if" a fire will burn or not. Since smoldering combustion is not currently addressed in this system, it would be inappropriate to apply FARSITE to simulate this type of fire behavior. The slower the actual fire behavior, the greater the potential for over prediction by Rothermel's surface fire equation (Finney 1997).

There are several indices that may be referred to in order to determine the appropriate application of FARSITE. For example, the 1000-hour fuel moisture index value of 13% in YNP may indicate the active fire season when fire behavior models like FARSITE may best be applied. ERC is another index that may be referred to, although this index fluctuates more frequently, and may be more appropriately used in conjunction with other indices like the 1000-hour fuel moisture.

Computer and Program Limitations

Although FARSITE does allow for certain mid-simulation manual adjustments, computer hard drive limitations prevent the efficient manipulation of this program. This program requires a significant amount of memory and hard drive space to operate, and does not allow for multitasking. Current PCs and laptop computers available to FBAs, Resource Managers, and students alike are barely capable of running this program to its full extent. Simulations may take several hours to complete, depending upon the resolution of input data and parameter settings, and no other programs may be run on the same computer during this time. Once a simulation is running, the user may have to reboot the program, using the Control-Alt-Delete option, in order to interrupt the simulation.

FARSITE use requires user knowledge and experience with GIS as well as fire behavior analysis. This program still has many shortcomings and can easily crash. Care must be taken to avoid crashing the entire computer, although it is difficult to anticipate what might cause this until the damage has been done. Becoming efficient at FARSITE with minimal technical support can be time consuming.

7.3 LOST CREEK FIRE PROJECTION

The projections of the Lost Creek Fire represent only a couple of possible scenarios given the best input data available at this time. Based on the analysis of the other fires, the adjustment factors were probably not even close to 1.0 for all fuel models. The primary fuel models involved in these simulations were 1 and 8. Fire management notes indicated that the grass fuels did not contribute to fire behavior on this fire, thus the adjustment factor for this fuel model would approach zero. Fuel model 8 on the other hand, could have either over or under predicted, depending on stand age and whether fuel conditions were truly representative of this fuel model. It is possible, therefore, that the average adjustment factor may have exceeded 1.0, based on the previous analysis.

The wind data input into this simulation may have varied greatly in both speed and direction from those experienced on scene. There is no way of knowing for sure what these winds may have been since the Tower climatological station did not record winds data. The Mammoth weather station, approximately 17 miles to the west northwest, was determined a more appropriate wind data source than the Coyote fire, which was noted by fire monitors to be influenced by the canyon terrain not present in the Lost Creek area.

Due to these and other limitations, it is not realistic to expect these simulations neither to actually predict what the fire would have done nor to interpret the actual threat to the Tower / Roosevelt developed area. At the time of this fire, and relevant management decisions, there was no way of knowing how much longer the active fire season would last. Therefore, it may be safe to assume that this fire did pose some threat to the development, given the unknown projection time period.

8.0 CONCLUSION

Due to the many errors inherent in the FARSITE model, results of simulation runs were not expected to be accurate. Multiple errors may mask each other, resulting in less observable error, or they may compound the overall error, resulting in large observable error. It may not be known exactly where these errors originate or how great each error is, but it must be assumed that some error exists even when not observable. FARSITE users must have a clear understanding of these limitations in order to make appropriate interpretations of the output.

Fuel mapping efforts are still preliminary and subject to significant inadequacies. As Keane et al.(1998) stated, the development of these layers should be thought of in terms of an ongoing process and not just a finished product. Technological advances, in addition to continued time and money spent on mapping efforts will increase the accuracy of these maps. It is also important to maintain updated maps incorporating ongoing management actions (e.g. fuels treatments or timber management) and wildfire activity that may alter fuels conditions.

There are a number of actions that can be taken to improve future FARSITE utilization. Additional mapping efforts should focus on areas of LP2 cover type to better refine fuel model 8 and 10 delineation. Efforts should also focus on capturing small-scale fuel breaks and discontinuity of fuels. Reassignment of the fuel model 5 to a non-fuel type should be followed up with further study to better determine subsequent fuel model classification and when these areas should be reclassified.

Weather data collection for the purpose of FARSITE utilization should address location and number of RAWS weather stations and fire monitors across the landscape as well as frequency of data collection to better capture temporal and spatial variation. As fires progress, these considerations must continually be reassessed to best fit the needs of the growing fire and changing conditions.

Due to preliminary data collection requirements and computer limitations, FARSITE is not necessarily quicker and easier to use than manual fire behavior predictions. This program is based on the widely used BEHAVE modeling system and accepted fire behavior models and may not provide enough additional support to deem its use necessary. The costs and benefits must be weighed prior to implementing FARSITE.

There are still many aspects of fire behavior modeling that need to be further understood and developed, especially to address fire behavior in a 3-dimensional landscape. Scientists are continually working toward updating fire behavior modeling.

FARSITE will be going through several improvements over the next few years, including improved user friendliness and program capabilities (Finney, Pers. comm.). Both BEHAVE and FARSITE will be replacing the fuel moisture model. Eventually, there is hope to replace Rothermel's crown fire model with new work in progress. Both models will also include models for calculating combustion of fuels behind the fire front and emission production (Finney and Andrews 1998, Andrews and Bevins 1998). Although this work is being accomplished quickly, there is still much testing to be done and this new version of FARSITE may not be released for a few more months, or longer (Finney, pers. comm.).

There are currently wind simulation models that address the effects of terrain on local wind patterns. The available resolution, however, is not detailed enough to consider an important addition to this model (Finney, pers. comm.). Future improvements in wind modeling may eventually benefit fire behavior modeling, especially in the 3-dimensional setting of FARSITE. Due to the technological requirements of these types of programs (computer space and time), however, it may be more realistic to keep these models separate.

Results of this study will not be greatly affected by these changes, as the overall effectiveness of FARSITE in the Yellowstone area will have been primarily established. More detailed analysis of crown fire modeling may be desired as well as new studies looking at the new models that will be added (e.g. post-frontal fuel combustion).

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